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Modelling of Integrated Traffic Networks Using the Integration Simulation Model

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Abstract: This report summarizes the development of a new modelling approach for integrated traffic networks. It describes how this development has resulted in a sophisticated traffic simulation model, called *integration* which has been tested, demonstrated, calibrated and validated to varying degrees.

The new approach provides an integrated modelling capability which can concurrently deal with congested and uncongested traffic flow conditions, freeway and arterial road links, real-time and fixed-time control strategies, and various types of driver information systems.

The report presents a description of the philosophy behind the model and its general concept. Subsequently, a description of the model inputs and outputs is outlined, before routines for generating synthetic O-D tables are introduced.

Subsequent sections of the report describe how the model was applied to the Burlington Skyway, how the model is linked to the Q-Route route guidance system, and what further developments are felt to be needed.

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1. INTRODUCTION

This report summarizes the development and demonstration of a new set of related traffic control models or tools. These models and tools have been specifically developed to cope with the new type of complex traffic congestion control problems that are or will be faced by virtually all major urban areas. This first chapter provides a brief background to the origin and nature of these new control problems, summarizes the most relevant literature on the subject to date, and outlines how the overall report and its related working papers have been organized.

a. Background to the Model Development

The continued growth of traffic congestion in virtually all urban areas has created a new set of traffic control problems which exceed those that have been dealt with to date in terms of both their scope, complexity, and scale. Consequently, there is a corresponding lack of tools to deal with them.

For example, in the past it could be considered that signalized traffic networks would operate with minimal oversaturation and that the controls that would be applied to deal with these undersaturated traffic flow conditions would be predominately fixed-time in nature. Instead, most of today's traffic signalized networks are routinely oversaturated and have queues which regularly spill back to block upstream intersections. In addition, the control strategies that may be required to deal with these conditions have become increasingly real-time in nature and require a dynamic solution approach, which cannot properly be evaluated or optimized using current static traffic signal models.

Similarly, freeway congestion had traditionally been viewed as a control problem whose main impact was confined to strictly the freeway right-of- way. Instead, it is now commonly accepted that both recurring and non-recurring freeway traffic congestion has a significant impact on both parallel and perpendicular arterials. Furthermore, it is also considered by many that these arterials have to play an active role in contributing to the solution of many types of freeway congestion problems. Unfortunately, traffic engineers are again ill equipped with appropriate tools to not only evaluate and quantify the existing problems, but to also develop and optimize the control strategies that may be required to make the most effective use of the available control hardware.

Compounding the above traffic control complexities is the recent emergence of new types of driver information systems. These systems may be able to assist drivers in either avoiding traffic congestion, or minimizing their exposure to it. In either case, these systems provide a unique opportunity to try to alleviate the impact of the growing traffic congestion. However, the degree of interaction that these systems must have with the already complex traffic control systems, provides a new series of control problems which to date have remained largerly unsolved, if not unaddressed.

b. Overall Objectives of Model Development

In view of the above new types of traffic control modelling requirements, a new type of modelling approach was proposed by Van Aerde(1985), which is described in detail in Van Aerde and Yagar(1988a and b). This new approach was intended to provide an integrated modelling capability which could concurrently deal with congested and uncongested traffic flow conditions, freeway and arterial network links, real-time and fixed-time control strategies, and various types of driver information systems. The approach was considered to be integrated, in the sense that a single model could concurrently model each one of these aspects, and could also deal with their often complex dynamic interactions.

The long term of objective of this model development was to develop a new model which could ultimately be used on a routine basis by any traffic engineer, who is reasonably conversant with both computers and traffic flow theory. However, in view of the rather different modelling approach that was considered and its largely unproven potential, more modest short and medium term goals were identified.

c. Immediate to Medium-Range Objectives

The short term goal, of the model development, was to develop the general modelling approach into a working traffic simulation model and to perform a series of tests on the model to demonstrate that it could deliver on some of its very promising features or expected capabilities.

To meet this short term goal, a simple hypothetical test network was coded, which consisted of a freeway and a parallel arterial. For this hypothetical test network a series of different integrated control strategies were demonstrated and the ability of the model to properly represent and objectively evaluate these strategies was illustrated.

The medium term goal of the model development was to demonstrate the modelling approach for a small but realistic integrated traffic corridor network. Not only would this demonstration indicate the feasibility of applying the model at such a scale, but it would also permit an illustration of the amount of effort that would be required to code, calibrate and apply the model. As a by-product, the medium term goal would also indicate if the integrated control results, which were obtained in the simpler hypothetical test network, would also apply to a more complex real network, where the cause and effect of certain traffic flow effects are more difficult to observe or explain.

d. General Benefits of Project

In general, the modelling development work has also served to encourage a Canadian base of expertise in an emerging new area of high technology application to traffic control problems. It has also helped raise the issues of integrated congestion control using new technologies amongst both the public and the responsible control agencies. In addition, the students who have worked on this project will be better equipped to deal with traffic congestion problems upon joining the work force, while the development has helped bring the Ministry of Transpor-

tation back to the forefront in terms of research, development, demonstration and application of advanced urban traffic control strategies.

c. Overview of the Report

This report summarizes a 2-Part research project into the development of this new modelling approach for integrated traffic networks. It describes how this development has resulted in a new traffic simulation model, called INTEGRATION, which has been tested, demonstrated, calibrated and validated to varying degrees.

Chapter 2 provides an overview of the new modelling approach, its concept, structure, philosophy and implementation in terms of the INTEGRATION model. This includes a brief discussion of how traffic flows, traffic assignment and various control models have been represented and why their implementation is, for a very wide range of applications, an improvement over existing methods.

Chapter 3 provides a summary of the coding and testing of the INTEGRATION model using the QNET hypothetical test network. Complete details as to how to code the model inputs, and interpret the model outputs are provided in Working Paper 1 (Appendix A), while a discussion of the application of this model, to evaluate integrated control strategies, is provided in Working Paper 2 (Appendix B).

Chapter 4 illustrates how the inputs to a model, such as INTEGRATION, can be developed from readily available FTMS detector data. It illustrates how the networks can be coded and how speed-volume relationships can be calibrated. To assist in the development of of the required synthetic origin-destination demand matrixes, from detector link counts, a new pre-processor was developed for the model. This pre-processor, called SODGE, is described in detail in Working Paper 3 (Appendix C).

Chapter 5 discusses how the model has been applied to MTO's Burlington Skyway FTMS to evaluate the potential effectiveness of different integrated traffic control strategies for a relatively simple freeway/arterial corridor. The effects of freeway incidents of varying durations are simulated and the potential benefits of having real-time signal control and/or dynamic route guidance under these conditions was evaluated. The detailed results of this analysis are provided in Working Paper 4 (Appendix D).

Chapter 6 indicates how the routing attributes of the INTEGRATION traffic control model can be utilized to form the information data base for a comprehensive route guidance system and how INTEGRATION can be used to act as a test bed for evaluating the potential benefits of route guidance systems under various conditions. The development and initial demonstration of such a system, which is called Q-Route, is summarized in this chapter and detailed in Working Paper 5 (Appendix E).

Chapter 7 summarizes the research and development to date, indicates the significant advances towards integrated control that have been made, and formulates a set of recommendations with respect to the types of further development that should take place. This summary

discussion focusses on the current capabilities and limitations of the model, and the type of modelling applications to which the model could be applied to within Ontario.

2. OVERVIEW OF THE MODELLING APPROACH

The original INTEGRATION modelling approach was developed by Van Aerde(1985) in response to a virtual absence of a suitable model for modelling freeway/arterial corridor control strategies during recurring and non-recurring traffic congestion ((Yagar,1983), (Van Aerde and Yagar,1987) and (Van Aerde, Yagar, Ugge and Case,1988)). Numerous simulation and/or optimization models were shown to be available, but none of these could satisfactorily model all the important attributes of each of the subnetworks involved.

a. Integrated Modelling Requirements

A closer look at the requirements of a model for integrated networks indicated that within large urban areas the traffic demands, queues, controls, flow rates, routings and incident occurrences vary virtually continuously. Consequently, it is nearly impossible to formulate a satisfactory steady-state solution to this problem. The inappropriateness of a steady-state solution is in direct conflict with the fundamental premise of most of the previous traffic network models, as all of these required all traffic related parameters to be constant for a finite time period (typically 15 minutes at a time).

For example, traffic signals could only be evaluated if a single cycle could be considered representative of all the cycles during this time period. Similarly, freeway flows could only be modelled if the flow rates, queue growth rates or the status of any incidents were considered to be constant for the entire time slice. Finally, the equilibrium traffic assignment could only be formulated if all demands, controls and flow rates were assumed constant for the entire period.

b. Basis of Proposed Solution Approach

In view of the dynamic nature of the problem to be modelled, a more dynamic modelling approach was formulated (Van Aerde,1985) and (Van Aerde and Yagar,1988 a and b). This approach intended to model traffic flows in terms of individual vehicles whose individual movements would be traced using a deci-second to deci-second time stepping approach. When each step is to be taken, any applicable controls, queues, and routing, capacity or other considerations are surveyed, and the vehicle's movements are updated accordingly.

As all entities are considered in terms of their instantaneous status, rather than their average characteristics over a finite time period (typically 15 minutes), the status of all of these entities can be changed continuously, either internal or external to the model. Consequently, the delay characteristics of the individual vehicles, which travel through the network to represent the network traffic flows, will react to these dynamic changes as they happen. This capability allows the model to consider real-time signal controls, traffic responsive ramp-metering, variable duration incidents and the impact of dynamic driver route guidance systems.

c. Simulation of a Typical Vehicle Trip Through the Network

The concept of the new traffic simulation model is perhaps best illustrated by tracing a vehicle's path on a typical trip through the network.

All traffic demands must be specified to the simulation model as departure rates which prevail for a finite period of time, ranging from a few minutes up to perhaps one or more hours, depending upon the variability in the traffic flows. These origin-destination demand rates are decomposed for each O-D pair into a series of individual vehicle departures at either uniform or exponential headways. When the simulation then starts, each vehicle is entered into the network at its appropriate departure time, and forwarded on the first link towards its destination.

Along its trip, each vehicle is delayed an amount of time equal to the non-queueing travel time along each link it utilizes. Upon arriving at the end of the link, the vehicle is then moved on to the next downstream link, unless some conditions restrict such a movement. A typical restriction could be a red indication at a traffic signal or ramp meter, a queue of vehicles which are already waiting to discharge from this link, an incident which blocks the entire road, or a queue spill-back condition from a downstream link which prohibits any additional vehicles from entering it.

When a number of downstream links are available to the driver at a network node, the downstream link appropriate to the driver's intended destination is selected according to a set of routing vectors. These routing vectors are a mathematical representation of what is considered to be the recommended route to travel from any network node to any of the possible destinations. The content of these routing vectors can be pre-specified, to reflect the general knowledge that drivers have of the best network routes. Alternatively, these vectors can be computed on- line based on the dynamic traffic conditions which are modelled within the network. Potentially, the routing vectors for some drivers could also be computed by an algorithm external to the model, which could reflect the centralized dissemination of system-optimum routings.

d. Simulation Statistics

The times at which each vehicle enters and exits each link are noted throughout the simulation. From these times, detailed travel time statistics can be derived as to the average link travel time, as well as any variation about this average. Similarly, statistics are also accumulated about any vehicles which reach their final destination. These statistics allow average trip times and the total number of arrivals to be directly compared for runs which represent different control scenarios.

During the execution of the simulation program, extensive graphics are made available to the user on a graphics monitor. These graphics indicate the network traffic flows, the status of any traffic signals or ramp meters, and/or the development of any queues. In addition, the status of each minimum path tree is also periodically indicated using on-screen plots of the minimum

path routes. At the conclusion of the runs, a series of intermediate and final statistics are available to indicate the network behaviour during the entire simulation.

3. ILLUSTRATION OF MODEL INPUTS AND OUTPUTS

In order to illustrate the fundamental types of data that are required to execute the INTEGRATION model, a hypothetical sample traffic network was coded. The coding of this network, which is called QNET, as well as the results of analyzing the simulation results for this network, are briefly described in this chapter.

a. Model Data Inputs

The main data inputs to the INTEGRATION simulation model consist of essentially 5 types of data, as illustrated in Figure 1a. These inputs are briefly summarized below and are detailed in Working Paper 1, which is a user's guide for the program.

Figure 1a illustrates that the coordinates of each network zone and node must be identified and entered into a master coordinates file. This file has a minimal impact upon the results of the traffic model, but is the key to the graphical network displays which can be generated on-screen or on a plotter. An example of such a display for the QNET network is provided in Figure 1b.

The link descriptor file indicates how the various network nodes are joined by the links, which represent the roads, streets and/or freeway segments to be modelled. Not only does this file indicate the start and end nodes of the link, but it also indicates the link properties, such as its freespeed, the number of lanes, the saturation flow rate, the type of signal control and the saturation flow reduction during congested conditions.

The third file provides the signal timings associated with each traffic signal in the network. This file provides a one line entry for each traffic signal, which indicates the maximum/minimum cycle times, the signal's network offset, the phase structure, and the initial phase timings. These timings are either maintained at a constant value throughout the simulation period, or they may only form the starting point for the subsequent real-time signal timing optimization process.

The fourth input data file provides information to the model about the origin-destination traffic demands that will be applied to the model. For each period, during which a given origin-destination demand flow rate is assumed to be constant, an entry is made into the O-D demand data file. This entry specifies the departure rate and the start/end times for this departure rate. Internal to the model, these departure rates are disaggregated into a series of individual O-D departures.

The final input data file to the model indicates the number of incidents that are to be modelled during a given simulation run. A single entry is provided for each capacity reduction event, which indicates the link affected, the start time and the end time of the event, as well as the effective reduction in number of available lanes. Any lane blockage which is removed to the

Figure 1 a: Integration Model Input Data Files.

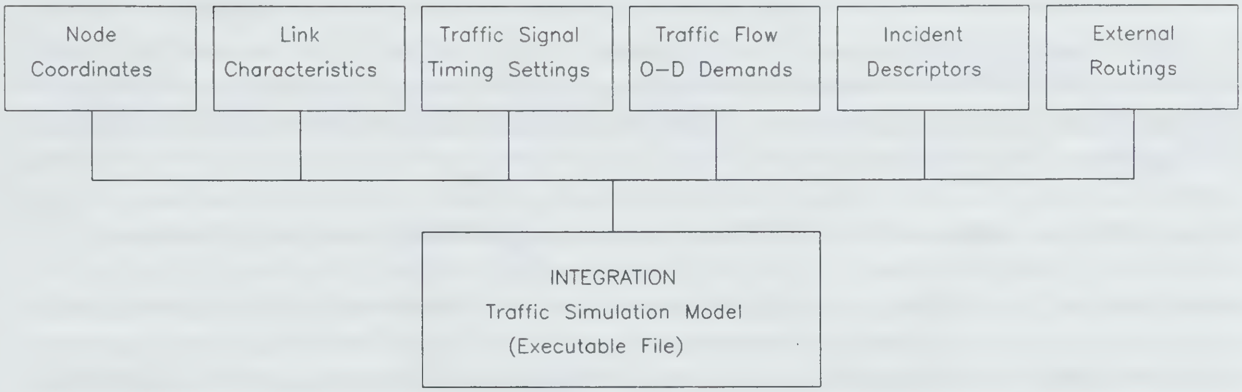
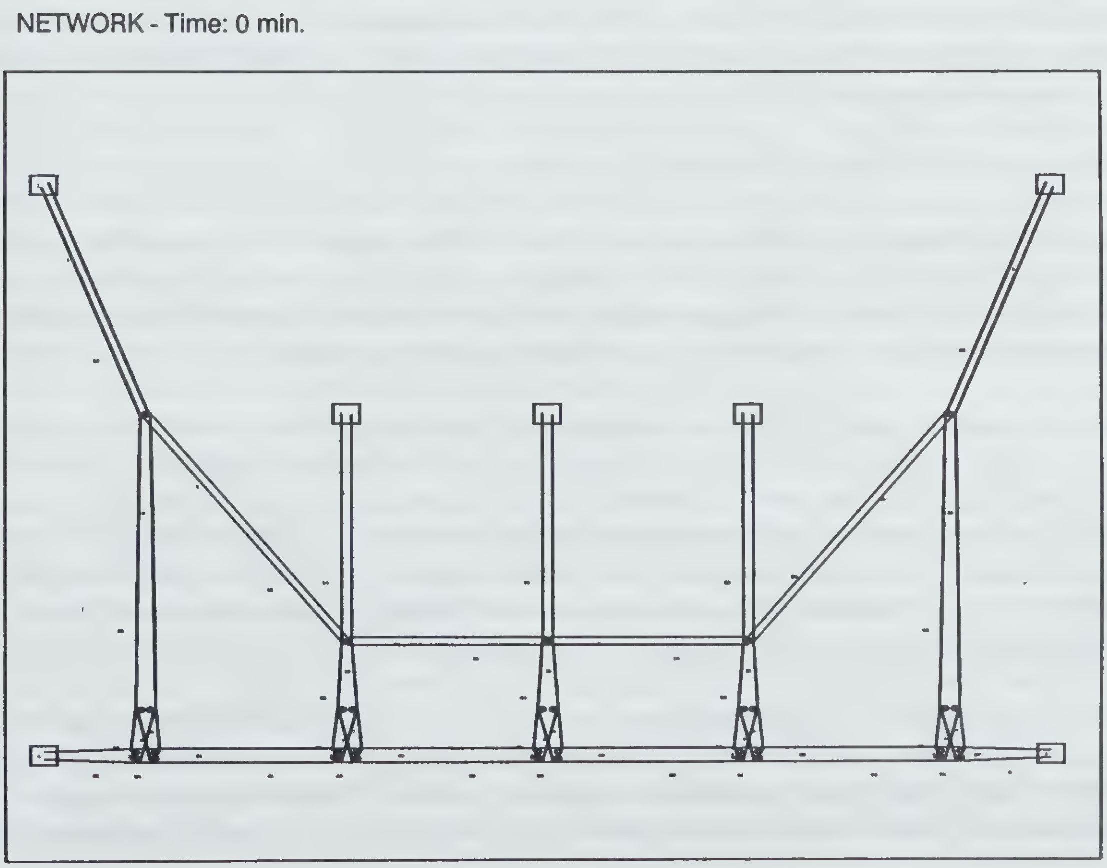


Figure 1 b: QNET Test Network Configuration



shoulder after some time, needs to be modelled as two separate incidents. The first would indicate a single lane blockage, while the vehicle was in the lane, while the second would indicate a partial lane blockage to reflect the remaining partial lane loss effect of having a vehicle parked on the shoulder.

b. Model Application to the Test Network

In order to test the capabilities of the Integration model and to refine some of its model components, the QNET test network was developed. This network was illustrated in Figure 1b, while a more detailed description of the network and the test results are provided in Working Paper 2 (Appendix B).

The test network consists of a major 4-lane freeway, a signalized 2-lane parallel arterial, and a number of 2-lane connectors to join the freeway and arterial at 5 locations. Each of the intersections of the parallel arterial and the connectors are signalized. The objective of this test network configuration was to demonstrate how INTEGRATION would model this type of corridor network in view of the fact that a signalized diversion route exists when a freeway incident occurs. Several potential diversion points exist and different O-D pairs can utilize alternate routes, depending upon the incident severity.

During the analysis of this test network, an incident was introduced on the freeway which blocked one lane in the eastbound direction. Different durations of this blockage were modelled and the consequent impacts on the network were traced. In particular, it was demonstrated that the model can successfully track the consequences of freeway incidents, model the consequent diversion and estimate the potential of providing real-time controls along the parallel diversion route.

c. Significance of Test Network Results

The test network analysis provides an initial look at the expected increases in delay for incidents of different durations. This provides an insight into the relationship between incident duration and network impact, while the results can also be interpreted as estimates of the expected benefits of improved (i.e. quicker) incident response.

The incident analysis also provides an indication of how many drivers would like to divert around the incident bottleneck. It also illustrates what this diversion implies in terms of an increased traffic load on the parallel arterial. In particular, the analysis identifies how much diversion is desirable and what the congestion consequences of this diversion will be on the affected diversion routes. Not only does the model account for the increased delay to the diverted traffic, but it also estimates the delay that will be imparted on those vehicles which were already utilizing the arterial, prior to the incident.

The test network model analysis also demonstrates the evaluation of different signal timing strategies. The performance of the existing signal timing plan be examined, and other alternative signal timing plans can be pre-evaluated as well. These strategies may involve coordination of all traffic signals on a common cycle length or the use of different optimum

cycle lengths at each intersection, without coordination. Finally, a built in optimizer within the model can be utilized to determine real-time traffic signal plans, based on on-line measurements of approach flows. Such testing can pre-evaluate or calibrate a general incident response signal control strategy, rather than simply evaluate a specific signal plan for a given incident.

4. DEVELOPMENT OF THE INPUT DATA FOR MODEL

The quality of analysis that is provided by any traffic model is usually limited by the availability of sufficient and appropriate data. In response to this concern, a technique was adapted to generate the required traffic demand and supply data from existing FTMS data sources. The demand generation technique and its preliminary testing using data from the Burlington Skyway network is detailed in Working Paper 3 (Appendix C), and summarized below.

a. Background to Development of New O-D Matrix Technique

In most traffic networks, the link traffic flows cannot be considered as independent demand data inputs, as the amount of traffic on these links is a function of the network characteristics and controls. For example, an incident or a diversion strategy may change the traffic flow patterns in the network, making it inappropriate to analyze the impact of these factors based on fixed link flows. Instead, it is more realistic to assume that origin-destination flow patterns of a network are fixed, allowing the specific link flows to be derived from them.

The difficulty in utilizing O-D data, rather than simply link flows, derives from the fact that these data are very difficult to obtain from direct surveys or observations. Instead, indirect methods have to be applied which back-calculate the most likely origin-destination matrix, based on link flow data. A technique, to perform such an analysis, was adapted from an existing and proven technique and was implemented in a model called SODGE. In addition, its inputs were made to be compatible with those of the Integration model. However, as corridor models require a sequence of O-D matrices, one for every 15 minute time period during the peak, rather than a single O-D matrix for the entire peak, an additional modification had to be made. This modification allowed for a recursive use of the synthetic O-D generation technique, in which the final result matrix from one time period is automatically forwarded as the seed for the solution search in the next iteration.

b. Results of the Tests of the Technique

The suitability of this sequential approach to generating synthetic O-D matrices for 15 minute time periods during morning peak periods was tested using data for the Burlington Skyway. A traffic network representation, which was coded to model the Burlington Skyway corridor, was utilized to derive the minimum path routes through the network, while detailed traffic counts from each detector station were summarized into 15 minute flow rates to be utilized in conjunction with SODGE.

Tests using these data indicated that the technique was able to successfully reproduce a given solution matrix, within a certain margin of error, and that the technique could adequately deal

with moderate changes in O-D patterns during the peak period. Sensitivities of these results to various initial conditions or stopping criteria were investigated, and these results were utilized to determine guidelines for subsequent use of the technique to generate real O-D matrices for the corridor, as outlined in Chapter 5 of this report.

5. APPLICATION TO THE BURLINGTON SKYWAY

In order to demonstrate the feasibility of applying the INTEGRATION model to a typical freeway/arterial corridor, to illustrate the availability of the required data, and to indicate the types of useful insights that the model could provide, the model was applied to analyze a series of incidents on the Burlington Skyway Corridor network. Details of this application are provided in Working Paper 4 (Appendix D), while the main steps and findings are summarized below.

a. Description of the Network

The Burlington Skyway Corridor network was selected for a number of reasons. First, it is a simple and relatively small freeway/arterial corridor in which there is a main freeway route and a single slower signalized arterial route. Second, this freeway route is exceptionally vulnerable to capacity reductions due to its grade, susceptability to winds and other environmental hazards, and the difficulty of gaining access to the incident site during an incident response. Finally, the network was selected as many of its loop detectors were on-line, such that detailed demand and supply data could be readily obtained.

The network location and the way it was coded are illustrated in Figure 2 a and b. As shown, only the southbound direction of the corridor was analyzed, as it was most heavily detectorized. It would have been interesting to also model both directions simultaneously, but the assumptions that the two directions have a minimal interaction effect on each other is likely to be valid for most conditions.

b. Generation of the Input Data

The network was coded using base maps from the Ministry of the Environment and data from the Burlington Skyway FTMS preliminary design report. In addition, field observations were made to assist in the coding of the network.

The capacities and speeds of selected network links were calibrated using the aforementioned FTMS data from the control centre. Speed- volume relationships were plotted and from these, the free-speed as well as the per lane capacity were derived.

The demand data was generated using the synthetic O-D generation routine, which was described in Chapter 4. Individual 30-second vehicle detector counts were combined to provide 15-minute link flow rates, and the rates, in conjunction with the network's minimum path trees were then used to generate synthetic origin-destination matrices for every 15-minute interval between 7:00 and 9:00 AM.

Figure 2 a: Location of Burlington Skyway FTMS.

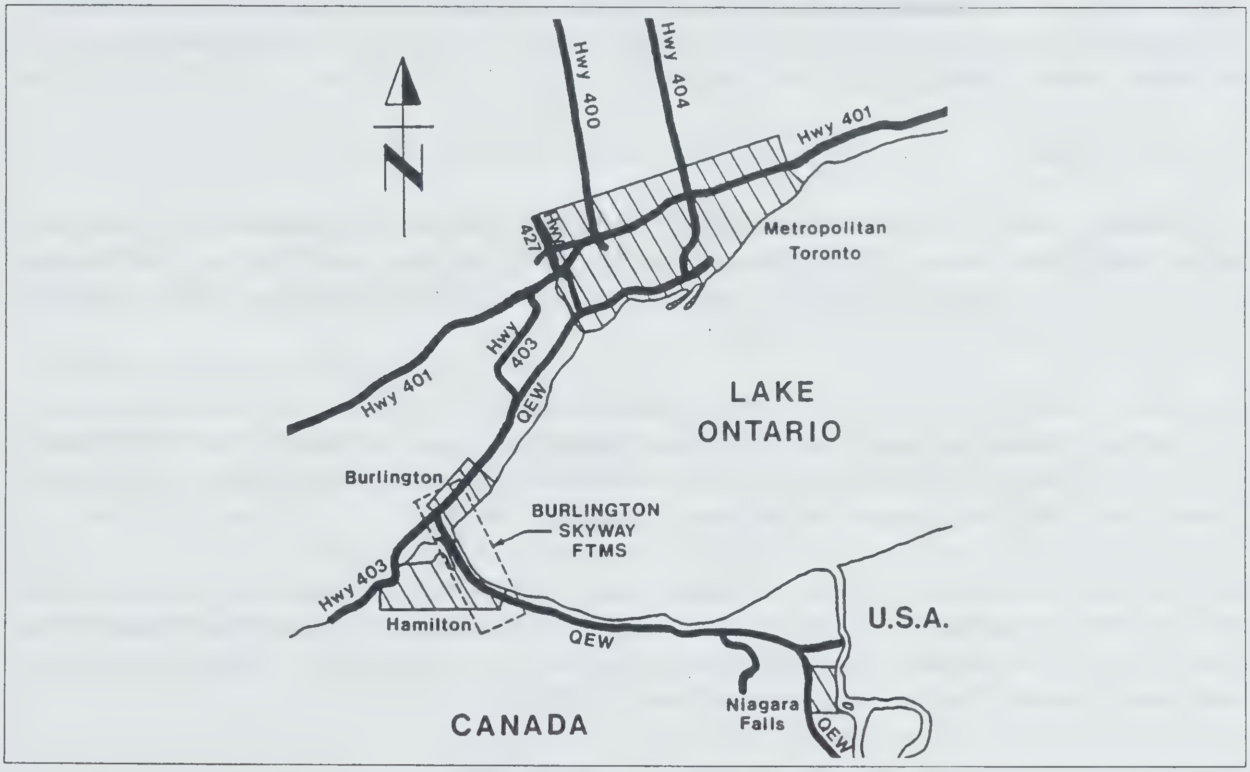
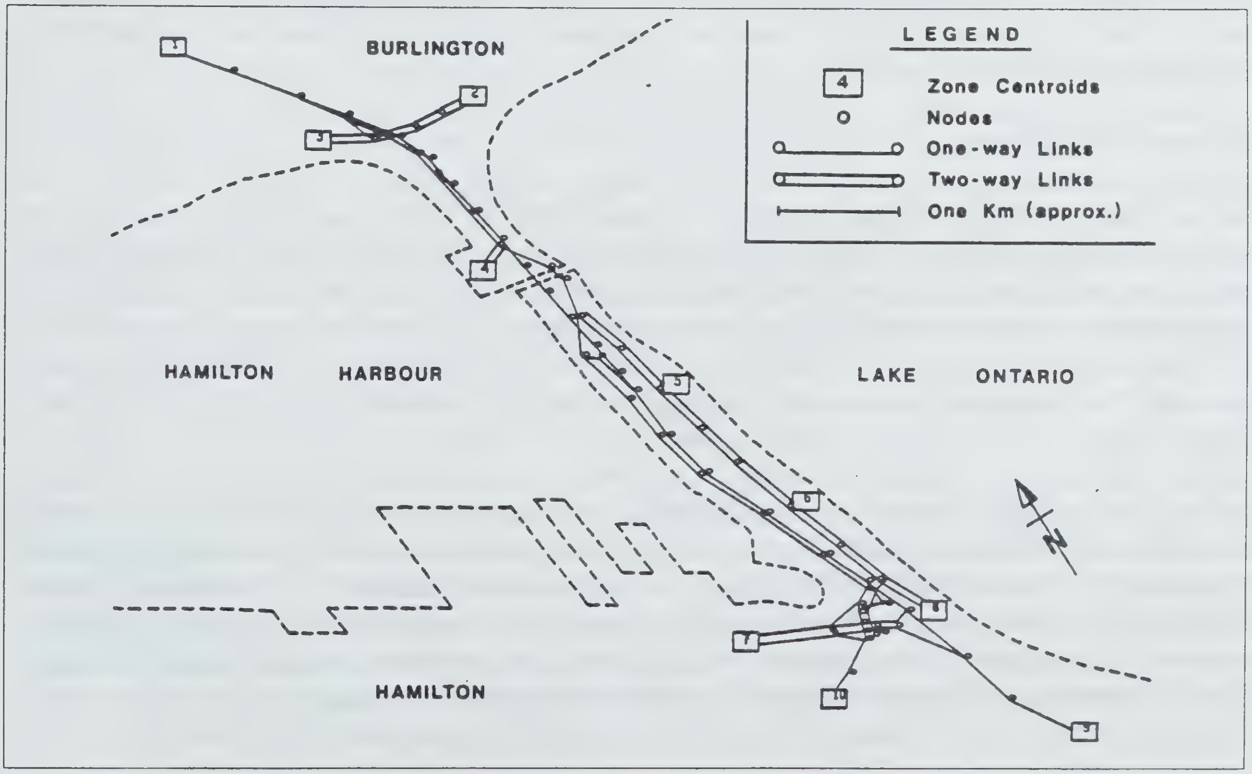


Figure 2 b: Burlington Skyway Coded Network



To validate the agreement between the original detector link flow counts, the estimated SODGE flow rates and the simulated INTEGRATION flow rates, a number of correlation plots were generated. These plots indicated a good general agreement between predicted and observed flow rates. However, a few small discrepancies between observed and simulated conditions remain under further investigation.

c. Analysis Results

Experiments, similar to those described for the QNET test network were repeated for the Burlington Skyway Network. Incidents of varying durations were modelled on the freeway and the diversion response of traffic, as well as the potential for retiming the traffic signals on the parallel arterial route were examined.

In general, it was found that for non-incident conditions, the opportunity for dynamic re-routing of traffic provides only a minimal additional benefit, in terms of a reduction in travel times. However, as increasing incident durations were considered, the benefits of increased dynamic re-routing of traffic became very significant.

The provision of real-time signal re-timing on the parallel arterials proved to provide more significant travel time savings than the re- routing option, for the initial non-incident situation. However, while the benefits of signal re-timing also increased for longer incident durations, these were less than those achieved through re-routing.

The scenario which considered both the re-routing of traffic and the re- timing of traffic signals in real-time, provided the greatest decrease in delay, for all incident scenarios. The benefits of such joint signal/routing optimization, during incidents, reduced the travel times to levels comparable to the travel times that were experienced for the non-incident scenario with no signal retiming or traffic rerouting.

d. Discussion of Results

The analysis of the Burlington Skyway using the INTEGRATION model showed that it is possible to generate the required supply and demand data, and that the final outputs of the model can be calibrated against these data. Secondly, the trial applications of the simulation showed that it is possible to simulate a network of the scale of the Burlington Skyway on an AT micro-computer at a ratio of real-time to simulated time of about 1:1. This indicates the potential to perform real-time control based on the Integration model using a faster microcomputer.

The application also illustrated that it is feasible to examine the interactions of a freeway and a signalized arterial during incident conditions. This evaluative capability not only permitted an analysis of what would happen if no response plan was available, but also allowed for a detailed evaluation of the effectiveness of the various components of each response plan. For example, not only could the benefits of independent signal re-timing and real-time rerouting of traffic be estimated, but their interactions could be examined as well.

Beyond the use of the model to establish the cost-effectiveness of specific static response plans, the model can also be utilized to compare the advantages of different types of dynamic response strategies for the same series of anticipated incidents. The latter analysis would permit one to examine if a given strategy is consistently better, or if a promising strategy can, under some circumstances, lead to very undesirable results.

6. ROUTING IMPLICATIONS OF CONTROL STRATEGIES

The routing nature of the INTEGRATION model permits a number of interesting investigations of both routing effects and routing strategies. These items are summarized below, while full details of this research are provided in working paper 5 (Appendix E).

a. Modelling Routing and Routing Strategies

The INTEGRATION traffic assignment technique assigns individual vehicles to the network, en-route to their destination, based on a series of routing vectors. These routings can be pre-specified externally or be computed internal or external to the model. The former would reflect the results of a survey, which had determined which routes people typically take through the network. In contrast, the latter could represent a dynamically optimized routing, which is computed based on real-time information about traffic flows, speeds and queues throughout the network. Such internally or externally computed routings would model the effect of providing drivers access to a real-time driver information or route guidance system. The latest version of INTEGRATION permits both types of routing concurrently for different drivers during a single model run.

b. Evaluation of Routing Strategies

The ability to model concurrently both off-line type of route selection and route selection based on real-time traffic information allows the model to be used to pre-evaluate the benefits of providing different types and amounts of route guidance. For example, the behaviour of traffic under conditions where no real-time routing data is available can be modelled by routing all drivers using the pre- determined routing vectors, regardless of how traffic conditions may actually change during a simulation run. Alternatively, if the routings are re-computed internal to the model based on real-time traffic information, the simulation run could estimate the different expected network delays for a scenario where all drivers have route guidance systems available to them.

This basic capability to model different driver routing behaviour permits an extensive and detailed estimation of the likely potential benefits of mature route guidance systems under different conditions. In addition, the capability to consider a mixture of guided and non-guided drivers allows the modeller to consider what fraction of these benefits are likely to be obtained as increasing numbers of vehicles become equipped with appropriate route guidance equipment. The analysis of these route guidance scenarios also allows one to examine what types of signal or ramp-metering control strategies may need to be developed to operate concurrently with route guidance. At present, these strategies are largely developed assuming that the link flows are known and predictable in advance. However, route guidance systems

are likely to provide for a more dynamic and less predictable set of traffic conditions in the network. Consequently, possible benefits of route guidance may be lost if current static signal control strategies start to perform more poorly than before.

The concurrent modelling of routing and traffic controls within INTEGRATION permits a preliminary evaluation of how these interactions will be developed and should be solved.

c. Dissemination of Routing Strategies using Q-Route

Concurrent to the activities associated with the pre-testing of potential routing strategies, research was also carried out to develop a system to disseminate route guidance information, which would be compatible with INTEGRATION. This system is called Q-Route, as detailed in Working Paper 5 (Appendix E). Its features which relate to INTEGRATION are summarized below.

The premise of Q-Route was that a model, such as INTEGRATION, could model the behaviour of a congested traffic network and determine from these conditions the optimum routings through the network. The Q-Route system could then disseminate these routing vectors to reach each driver within his own vehicle and indicate to him which routes he should follow. If the driver then follows this routing, and the INTEGRATION model knows how many of such drivers are following its instructions, the simulation model could then also model what would happen to this mixture of routed and non-routed drivers.

To examine the feasibility of such a system, a prototype was developed at Queen's University and the required data bases were setup for the Greater Kingston Area. Preliminary tests demonstrated the feasibility of this approach as a tool for providing static routing, if the system is autonomous, or as a tool for dynamic routing, if the system is linked to a central computer using a two-way communications link (by cellular phone).

Subsequently, a macro traffic network was set up for the Greater Toronto Area, which included all the major freeways, highways and arterials in the region. This test network was utilized in conjunction with Q-Route in the laboratory to test the feasibility of implementing a network of this size within Q-Route. These tests indicate that this size of application is definitely possible, but that some important issues related to the data acquisition and dissemination remain outstanding.

d. Traffic Control Implications of Prototype Tests

The prototype tests of Q-Route indicated that it is definitely possible to link a comprehensive traffic control model such as INTEGRATION to a route guidance system such as Q-Route. The link from INTEGRATION to Q- Route can provide for improved dynamic route guidance information to the drivers, while the link from Q-Route to INTEGRATION allows the control system to better deal with any feedback effects that will be created when a significant number of drivers will be routed.

7. CONTRIBUTIONS AND FUTURE RESEARCH

The 2-part research project described and documented in this report has taken a general outline for a modelling approach and developed it into a model, called INTEGRATION, whose capabilities were demonstrated using a hypothetical as well as an actual test application. While a number of model aspects require further examination and testing, the research to date has clearly demonstrated the significant capabilities that exist within the INTEGRATION model to address a number of very important traffic control issues.

a. Current Capabilities of Integration

The INTEGRATION model at present is capable of modelling a series of incidents within an integrated freeway/traffic signal network. The direct impact of this incident can be measured in terms of increased travel times of the affected link, and in terms of the indirect impact of increased travel times on the diversion routes. In addition, either precalculated signal timing plans can be evaluated or the use of real-time signal re-timing can be considered. In each case, the model provides delay summaries on each link by itself, or for all trips with the same specific origin-destination.

b. Recommendations for Further Work

The main area of the model requiring further work is the generalization of the model to deal more easily with other, larger networks. At present, the microcomputer version is restricted to use 640K of memory, which limits the networks to the size of the Burlington Skyway. However, recent advances in microcomputer compilers would allow this barrier to be broken, and consequently permit larger scale applications of the model.

Such larger applications of the model would also permit an investigation to determine if the general findings, regarding the benefits of dynamic route guidance and real-time signal control during incidents, can be generalized to larger networks where multiple alternative routes exist and where some of these alternate routes may already be congested.

A similar evaluation should be performed of the findings regarding the potential for driver information systems. In particular, the implications of different percentages of drivers with in-vehicle route guidance systems should be determined. This would indicate if the benefits of route guidance will be proportional to the percentage of drivers that participate in the guidance system.

REFERENCES

Van Aerde,M. (1985), Modelling of Traffic Flows, Assignment and Queueing in Freeway/Traffic Signal Integrated Networks, Ph.D. Thesis, Dept. of Civil Engineering, Univ. of Waterloo.

Van Aerde,M. and Yagar,S. (1988a), Modelling Dynamic Integrated Freeway/Traffic Signal Networks: Problems and Proposed Solutions, Transportation Research A, Pergamon Press.

Van Aerde,M. and Yagar,S. (1988b), Modelling Dynamic Integrated Freeway/Traffic Signal Networks: A Proposed Routing-Based Approach, Transportation Research A, Pergamon Press.

Van Aerde,M. and Yagar,S. (1987), Review of Freeway Corridor Traffic Models, Ontario Ministry of Transportation and Communications Report, TDS-87-02, 75 pp.

Van Aerde,M., Yagar,S., Ugge,A. and Case,E.R.(1988), A Review of Candidate Freeway/Arterial Corridor Traffic Models, Transportation Research Record 1132, p. 53-65, Transportation Research Board.

APPENDIX A:

INTEGRATION-1: A MODEL FOR SIMULATING INTEGRATED TRAFFIC NETWORKS

USER'S GUIDE VERSION 1.1

M. Van Aerde, J. Voss, and G. MacKinnon

ABSTRACT

This user's guide demonstrates the use of the Integration model and indicates how its data inputs may be set up, and how its outputs should be interpreted. The manual describes these operations through the use of a sample network, which is coded on the accompanying demonstration disk as the QNET network.

In addition to illustrating the basic operation of the model, the user's guide also indicates how various types of typical traffic engineering problems can be addressed using this demonstration network problem.

1. INTRODUCTION

The Integration-1 traffic simulation model was developed to analyze a number of specialized problems related to integrated traffic networks, real-time traffic control and route guidance systems.

This guide describes the fundamentals of this model and indicates how they can be utilized to examine some very sophisticated traffic control problems. The latter is demonstrated through the discussion of a sample model application which is included on the **INTEGRATION-1 DEMO** disk. This demo version of the model is coded in Turbo Basic and can be run on most IBM compatible microcomputers. A full FORTRAN version of the model is also available, but it requires the use of a 386 type of microcomputer with at least 2Mb of memory.

a. Background

A number of Ontario's busiest traffic networks consist of a mixture of both freeway sections and traffic signal controlled surface streets. During peak traffic conditions and/or incident situations, congestion on one component of these networks will often spill over onto an adjacent network component, such that these networks cannot be considered or controlled in isolation, but need to be treated as an integrated unit.

In other words, freeway control problems need to be examined in light of their impact on parallel arterials, while traffic signal problems may have to be considered in view of the surrounding freeways.

b. Today's Status of Integrated Control

Despite the obvious need for integrated control, to date there has been a general lack of models which can appropriately model freeways, traffic signals, and the routing/diversion between them. Most existing models concentrate either on one network or the other, and consequently fail to model their interactions.

In response to this need for improved modelling of integrated networks, a modelling approach, called Integration-1, was developed. This approach has not only shown considerable promise in terms of providing improved integrated control, but also may provide the key to solving a number of problems related to real-time control and route guidance applications. The initial Integration-1 modelling approach has recently been adapted for third party use, and this User's Guide provides the necessary information to facilitate such use.

c. The Objectives of the Guide

The User's Guide is an initial document to assist traffic engineers in the analysis of integrated traffic networks through the application of the Integration-1 model. It is anticipated that the model could be effective as both a teaching and a research tool. To this end, the fundamental modelling approach of Integration-1 is first summarized. Subsequently, the model's required

data inputs are described, and the steps involved in running the model are illustrated using a sample model application which is included on the **INTEGRATION-1 DEMO** disk.

d. Hardware Requirements

In order to provide the greatest possible access to the Integration model, the demo disk has been set up to run on virtually any microcomputer with at least 512K and a single floppy drive. However, the program should ideally be run on a microcomputer with a math co-processor, a EGA type of graphics screen, 640k of memory and a hard disk for storing the output files. This latter configuration is much faster and convenient.

A full version of the program is also available which will only run on a 386 type of microcomputer, which is equiped with a 80387 math co-processor and at least 2 Mb of memory. This version is much faster than the demo and can utilize upto 16 Mb of expanded memory. The inputs/outputs to both the demo version and the full version are identical, except for the network size.

e. References to Other Integration Applications

Users of the Integration model, who are interested in further background reading should refer to the references indicated below.

More information about integrated control, models for integrated networks and the difficulties in evaluating such networks can be found in Yagar(1983), Van Aerde(1985), Van Aerde and Yagar(1988), Van Aerde, Yagar, Ugge and Case(1988), or Van Aerde and Yagar(1988 a and b).

Examples of the types of traffic control applications that the Integration model can be used for can be found in Van Aerde, Voss, Ugge and Case(1989), Van Aerde, Voss and Blum(1989), and Rakha, Van Aerde, Case and Ugge(1989).

f. Overview of the Guide

Chapter 1 of this guide provides a quick overview of the guide and indicates how the demo disk can be run to analyze a small sample network.

Chapter 2 indicates how the model inputs for this small sample network are set up, while Chapter 3 indicates how the various model outputs can be interpreted.

Chapter 4 provides some summary notes on the use of the model for other types of networks.

2. OVERVIEW OF MODELLING APPROACH

In order to provide the user with a better feel for the operation of the model, this section describes a few aspects of the modelling approach in greater detail and provides references to related documents and publications where further details can be found. In addition, this section reports on a sample network for which the traffic model was tested.

a. Basic Design of the Integration-1 Model

Due to the different characteristics of traffic flow that need to be modelled on freeways and at traffic signals, Integration-1 analyzes traffic flows in terms of vehicles which are individual entities. This microscopic approach permits a traffic flow representation which is not only common to both types of component networks, but also permits a continuous dynamic queueing-based traffic assignment(Van Aerde and Yagar, 1987b).

The common traffic flow representation is critical to modelling all network components in a consistent and compatible fashion, while the queueing-based dynamic traffic assignment technique is essential to dealing with diversion and re-routing of traffic during congestion and in response to any incidents.

b. Reasons for Considering Individual Vehicles

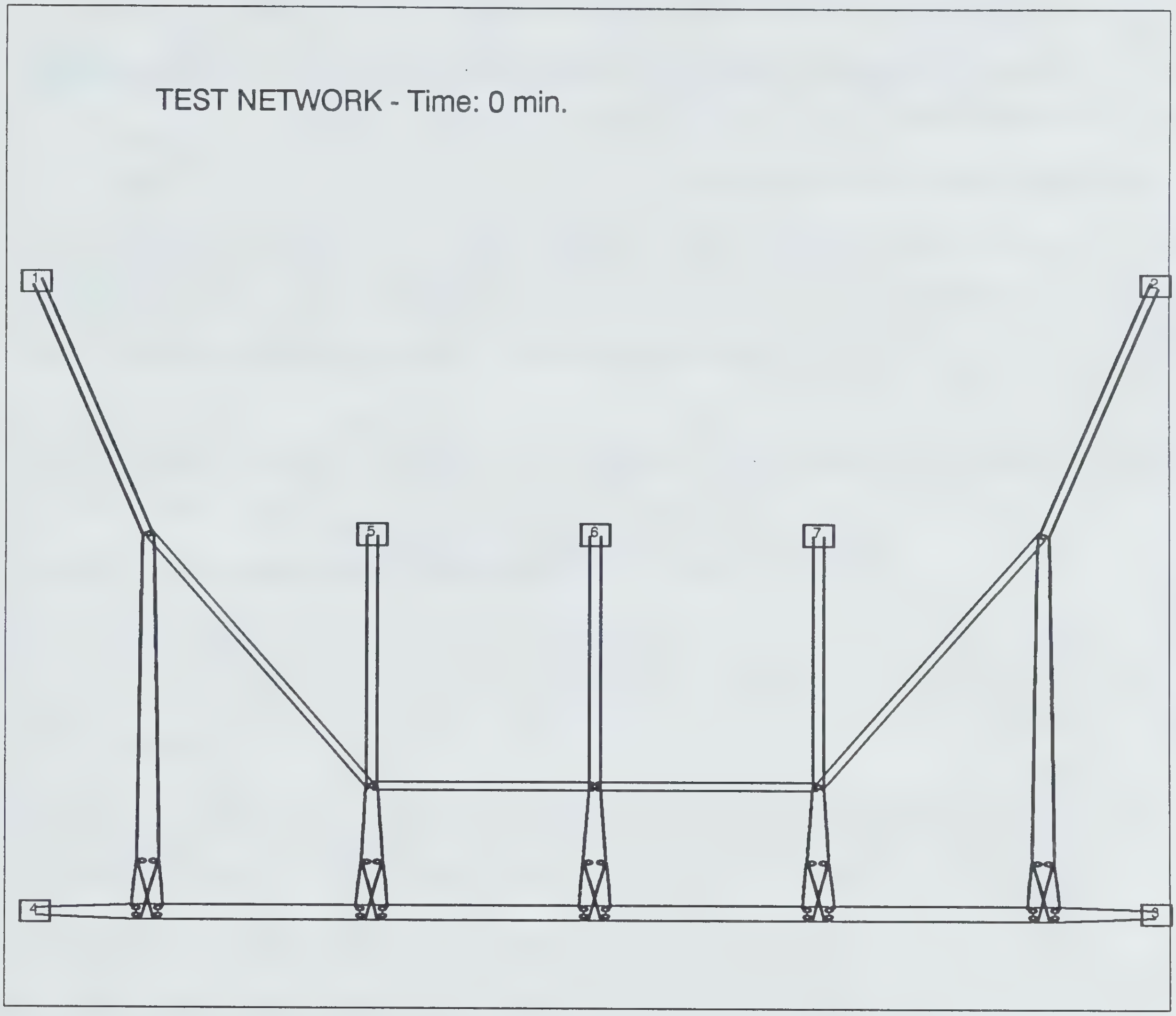
The model's consideration of individual vehicles is primarily for purposes of improving the analysis resolution during the model's internal calculations and does not necessarily require the user to collect or input data at the individual vehicle level. Instead, traffic flow characteristics and traffic demands can be specified by the user at an aggregate level, leaving it to the model routines to derive the more microscopic measures.

c. Test Network 1: QNET

A test network called QNET was developed to demonstrate the execution of the model and illustrate some of its features. The network consists of 7 origin/destination zones, 35 additional nodes and 70 links and represents a typical integrated network configuration. As shown in Figure 1, a high speed freeway as well as a parallel arterial are available for travel across the network. In addition, various connectors permit diversion between the freeway and the arterial at a number of selected places.

The sample model runs consider both non-incident and incident traffic conditions. For the incident situation, the model indicates that when an incident occurs on the freeway, which produces significant queueing at the bottleneck, a considerable amount of traffic will be diverted around the incident site. This application is also used to demonstrate the model's capabilities for evaluating the impacts of incident response time on both link travel time and o/d travel times.

Figure 1: Configuation of Small Integrated Test Network



d. Running the DEMO Disk

While the next chapters will discuss the various data inputs that are required to run the model and the various model outputs, it is instructive at this time to discuss the **INTEGRATION-1 DEMO** disk.

To run the Demo disk one simply needs an IBM-PC or compatible microcomputer with at least 512K of memory. The use of a math co- processor (8087 chip) is preferred as it will considerably speed up the running, but it is not required. Its availability is automaticaly detected.

To properly display the graphics one needs an EGA (Enhanced Graphics Adaptor) or VGA type of colour graphics monitor. A standard CGA Colour graphics monitor may also be used, but the resulting graphics may only be of marginal quality.

To run the **INTEGRATION-1 DEMO**, place the disk in the current logged on drive (or copy all the files on the **DEMO** disk to the hard disk) and enter the following:

INTGRAT2 RUN1.DAT <RETURN>

Table 1 shows the files contained in RUN1.DAT. These are the input data files that are expected on a sub-directory called INPUT on the current logged on drive. The last filename, RUN1.LST, is the output filename. Output files are written to a sub-directory called OUTPUT which is expected to have been previously created on the current logged on drive. The simulation time will be 3600 seconds.

Note that with the use of a batch file as the input file it is possible to create a DOS batch file

Table 1: RUN1.DAT - Integration-1 Batch File

```
QNET1.dat
QNET2.dat
QNET3.dat
QNET4.dat
QNET5.dat
QNET6.dat
RUN1.lst
```

that will run the Integration-1 model a number of times with different files while unattended. All that is necessary is that each different run be sent to a new output file. The input files can be changed or be kept the same, as may be desired.

3. MODEL INPUTS

To simulate an integrated traffic network, the Integration-1 model requires 6 primary types of data. These are for convenience purposes separated into 6 different files, labled QNET1.DAT thru to QNET6.DAT, and contain the following information:

QNET1: Node coordinates for graphics purposes (x and y values)
QNET2: Link descriptor file (length, location, type and lanes)
QNET3: Signal timing plan (cycle length, green times and offsets)
QNET4: Vehicle departure file (dept time, origin and destination)
QNET5: Incident descriptor file (start,end, location, severity)
QNET6: Minimum path trees (nodes to which vehicles travel)

These files are coded as ASCII characters in a tabular format and can be generated/modified using any standard editor or wordprocessor (in non- document mode). The functions and contents of the various files are described below in sections "a" through to "f", respectively.

a. QNET1: Node coordinates for graphics purposes (x and y values)

The file illustrated in Table 2 lists the x and y coordinates of all the nodes in the network. In the file header, the first number indicates the number of nodes, the second the number of zones, and the final number indicates the highest node number (in the case the node numbers are not continuous).

The X-Y coordinates are assumed to be specified in meters and should fall within the x and y min/max ranges previously specified in the second line of the file. The node type is either 1 for nodes which are also zone centroids and 2 for nodes which are not zone centroids.

b. QNET2: Link characteristic and descriptor file (length, location, type and lanes)

The link descriptor file, as illustrated in Table 3, lists the start and end nodes of each link in the network, its length, speed, and saturation flow rate per lane. In addition, a the saturation flow reduction for congested conditions, the number of lanes and a qualitative descriptor are also provided. Note that the links are sorted according to their end node, which is required for the tree building algorithm.

While link-specific free speeds are provided directly, the link capacity is calculated indirectly from the number of lanes and the saturation flow rate per lane, as follows:

Capacity = " capacity per lane" * "number of lanes"

The speeds at any traffic volume level can be calculated with reference to the above capacity and the free-speeds specified for each link.

Table 2: QNET1.DAT Specifying Node Coordinates

```
42     7    44
500 11500 500 4000
 1    1000   3500  1
 2   11000   3500  1
 3   11000   1000  1
 4    1000   1000  1
 5    4000   2500  1
 6    6000   2500  1
 7    8000   2500  1
10    2000   2500  2
11    4000   1500  2
12    6000   1500  2
13    8000   1500  2
14   10000   2500  2
15    1950   1200  2
16    2050   1200  2
17    1900   1015  2
18    2100   1015  2
19    1900    985  2
20    2100    985  2
21    3950   1200  2
22    4050   1200  2
23    3900   1015  2
24    4100   1015  2
25    3900    985  2
26    4100    985  2
27    5950   1200  2
28    6050   1200  2
29    5900   1015  2
30    6100   1015  2
31    5900    985  2
32    6100    985  2
33    7950   1200  2
34    8050   1200  2
35    7900   1015  2
36    8100   1015  2
37    7900    985  2
38    8100    985  2
39    9950   1200  2
40   10050   1200  2
41    9900   1015  2
42   10100   1015  2
43    9900    985  2
44   10100    985  2
```

LINE 1:
Numnodes: Number of nodes listed
Numzones: Number of zones listed at start of node list
Mnodenum: Number of the highest node number utilized

LINE2:
xmin : x-coordinate of left border of graphics window
xmax : x-coordinate of right border of graphics window
ymin : y-coordinate of lower border of graphics window
ymax : y-coordinate of upper border of graphics window

ALL OTHER LINES:
Nodenum: Node number
x : x-coordinate of the node location
y : y-coordinate of the node location
NZ : Node/Zone identifier (1 if node is also zone centroid)

Table 3: QNET2.DAT Link Descriptor File

70

10	1	1.414	70	2000	1.00	2	101	1	TO-ZONE1
14	2	1.414	70	2000	1.00	2	101	1	TO-ZONE2
44	3	0.9	70	2000	1.00	2	101	1	TO-ZONE3
17	4	0.9	70	2000	1.00	2	101	1	TO-ZONE4
11	5	1.000	70	2000	1.00	2	101	1	TO-ZONE5
12	6	1.000	70	2000	1.00	2	101	1	TO-ZONE6
13	7	1.000	70	2000	1.00	2	101	1	TO-ZONE7
16	10	1.300	50	1400	1.00	2	1	2	1ST AVENUE NB
11	10	2.236	60	1600	1.00	1	1	1	KINGSTON RD WB
1	10	1.414	70	2000	1.00	2	1	1	FR-ZONE1
12	11	2.000	60	1600	1.00	1	2	1	KINGSTON RD WB
10	11	2.236	60	1600	1.00	1	2	1	KINGSTON RD EB
22	11	0.300	50	1400	1.00	1	2	2	2ND AVENUE NB
5	11	1.000	70	2000	1.00	2	2	2	FR-ZONE5
28	12	0.300	50	1400	1.00	1	3	2	3RD AVENUE NB
11	12	2.000	60	1600	1.00	1	3	1	KINGSTON RD EB
13	12	2.000	60	1600	1.00	1	3	1	KINGSTON RD WB
6	12	1.000	70	2000	1.00	2	3	2	FR-ZONE6
12	13	2.000	60	1600	1.00	1	4	1	KINGSTON RD EB
14	13	2.236	60	1600	1.00	1	4	1	KINGSTON RD WB
34	13	0.300	50	1400	1.00	1	4	2	4TH AVENUE NB
7	13	1.000	70	2000	1.00	2	4	2	FR-ZONE7
40	14	1.300	50	1400	1.00	2	5	2	5TH AVENUE NB
13	14	2.236	60	1600	1.00	1	5	1	KINGSTON RD WB
2	14	1.414	70	2000	1.00	2	5	1	FR-ZONE2
10	15	1.300	50	1400	1.00	2	101	1	1ST AVENUE SB
19	16	.200	50	1400	1.00	1	101	1	OFF RAMP QUEEN'S WAY EB
18	16	.200	50	1400	1.00	1	101	1	OFF RAMP QUEEN'S WAY WB
15	17	.200	50	1400	1.00	1	101	1	ON RAMP QUEEN'S WAY WB
18	17	.200	110	2000	0.85	2	101	1	QUEEN'S WAY WB
23	18	1.800	110	2000	0.85	2	101	1	QUEEN'S WAY WB1
4	19	.900	70	2000	1.00	4	101	1	FR-ZONE4
15	20	.200	50	1400	1.00	1	101	1	ON RAMP QUEEN'S WAY EB
19	20	.200	110	2000	0.85	2	101	1	QUEEN'S WAY EB
11	21	0.300	50	1400	1.00	1	101	1	2ND AVENUE SB
25	22	.200	50	1400	1.00	1	101	1	OFF RAMP QUEEN'S WAY EB
24	22	.200	50	1400	1.00	1	101	1	OFF RAMP QUEEN'S WAY WB
21	23	.200	50	1400	1.00	1	101	1	ON RAMP QUEEN'S WAY WB
24	23	.200	110	2000	0.85	2	101	1	QUEEN'S WAY WB
29	24	1.800	110	2000	0.85	2	101	1	QUEEN'S WAY WB2
20	25	1.800	110	2000	0.85	2	101	1	QUEEN'S WAY EB1
21	26	.200	50	1400	1.00	1	101	1	ON RAMP QUEEN'S WAY EB
25	26	.200	110	2000	0.85	2	101	1	QUEEN'S WAY EB
12	27	0.300	50	1400	1.00	1	101	1	3RD AVENUE SB
31	28	.200	50	1400	1.00	1	101	1	OFF RAMP QUEEN'S WAY EB
30	28	.200	50	1400	1.00	1	101	1	OFF RAMP QUEEN'S WAY WB
27	29	.200	50	1400	1.00	1	101	1	ON RAMP QUEEN'S WAY WB
30	29	.200	110	2000	0.85	2	101	1	QUEEN'S WAY WB
35	30	1.800	110	2000	0.85	2	101	1	QUEEN'S WAY WB3
26	31	1.800	110	2000	0.85	2	101	1	QUEEN'S WAY EB2
27	32	.200	50	1400	1.00	1	101	1	ON RAMP QUEEN'S WAY EB
31	32	.200	110	2000	0.85	2	101	1	QUEEN'S WAY EB
13	33	0.300	50	1400	1.00	1	101	1	4TH AVENUE SB
37	34	.200	50	1400	1.00	1	101	1	OFF RAMP QUEEN'S WAY EB
36	34	.200	50	1400	1.00	1	101	1	OFF RAMP QUEEN'S WAY WB
33	35	.200	50	1400	1.00	1	101	1	ON RAMP QUEEN'S WAY WB
36	35	.200	110	2000	0.85	2	101	1	QUEEN'S WAY WB
41	36	1.800	110	2000	0.85	2	101	1	QUEEN'S WAY WB4
32	37	1.800	110	2000	0.85	2	101	1	QUEEN'S WAY EB3
33	38	.200	50	1400	1.00	1	101	1	ON RAMP QUEEN'S WAY EB
37	38	.200	110	2000	0.85	2	101	1	QUEEN'S WAY EB
14	39	1.300	50	1400	1.00	2	101	1	5TH AVENUE SB
43	40	.200	50	1400	1.00	1	101	1	OFF RAMP QUEEN'S WAY EB
42	40	.200	50	1400	1.00	1	101	1	OFF RAMP QUEEN'S WAY WB
39	41	.200	50	1400	1.00	1	101	1	ON RAMP QUEEN'S WAY WB
42	41	.200	110	2000	0.85	2	101	1	QUEEN'S WAY WB
3	42	1.150	70	2000	1.00	4	101	1	FR-ZONE3
38	43	1.800	110	2000	0.85	2	101	1	QUEEN'S WAY EB4
39	44	.200	50	1400	1.00	1	101	1	ON RAMP QUEEN'S WAY EB
43	44	.200	110	2000	0.85	2	101	1	QUEEN'S WAY EB

FIRST LINE:

Numlinks:	Number of links listed in this file

ALL OTHER LINES:

Start node:	Node which represents the start of the link
End node :	Node which represents the end of the link
Length:	Length of the link (kilometres)
Free speed:	Free speed for the link (km/h)
Basic sat flow:	Basic free flowing saturation flow (vph)
Congested factor:	Saturation flow reduction for queueing (fraction)
Num. Lanes:	Number of lanes on link(integer).
Signal Number:	Number of traffic signal which controls this link
Phase Number:	Number of the phase of the above signal for this link.
Link Name:	Descriptive name of the link

The extent of any signalization or ramp metering is specified with reference to a traffic signal number and phase number. The traffic signal number is specified with reference to the timings in the signal file QNET3, while the phase number allows the appropriate phase timing to be picked up. Any non-signalized links are indicated as belonging to traffic signal 101.

A coefficient, which indicates the reduction in saturation flow when traffic flow breaks down, is provided to account for the fact that the saturation flow rate for congested conditions is lower than for uncongested conditions on freeways. For example, for a high grade divided freeway which has a basic saturation flow per lane of 2000 veh/hr, a coefficient of .85 indicates that the saturation flow per lane drops to 1700 vph = 2000 vph * .85, following the occurrence of a traffic jam.

c. QNET3: Signal timing plan parameter settings (cycle length, green times and offsets)

Table 4 lists the signal timing plans that are in effect during the simulation period. The signal timings are specified in terms of the cycle length, offset of the start of phase 1, the number of phases, and the start times and end times of the green intervals for each phase. In addition, the lost times associated with each phase are provided.

The model structure allows up to 8 phases at each traffic signal. The timings can be coordinated using a common cycle length, or can be run in isolation using different cycle lengths. The choice between these alternatives, or any combinations thereof, need not be stated explicitly, but is rather implicit in the signal timing specification.

When the automatic cycle and phase split optimization option is utilized, only the offsets and the lost times specified in the original signal timing plan file are kept constant. The other timing plan parameters are optimized every signalopt seconds based on an running exponential

Table 4: QNET3.DAT Signal Timing Plan File

FIRST LINE:

Numsignals:	The number of signals listed.
Signalopt:	Seconds between each signal optimization

ALL OTHER LINES:

Signal number:	The number of the signal
Cycle Time:	The duration of the cycle time (seconds)
Mincycle:	The minimum cycle time allowed (seconds)
Maxcycle:	The maximum cycle time allowed (seconds)
Offset Time:	The relative offset of phase 1 (seconds)
Number of Phases:	Number of phases at the signal
Phase start:	Start time of phase (seconds)
Phase end:	End time of phase (seconds)
Lost time:	Lost time of phase (seconds)

```
5 180
1 60 30 120 0 2 0 36 4 40 56 4
2 60 30 120 0 2 0 36 4 40 56 4
3 60 30 120 0 2 0 36 4 40 56 4
4 60 30 120 0 2 0 36 4 40 56 4
5 60 30 120 0 2 0 36 4 40 56 4
```

average of the upstream traffic inflow rates. The procedure utilized for the signal timing plan optimization allocates green time based on the approach's volume/saturation flow ratios. This approach follows the Canadian Capacity Guide for Signalized Intersections which assumes that the start loss equals the end gain.

d. QNET4: Origin-Destination Traffic Demand file (dept time, origin and destination)

Any traffic demands are specified to the model in terms of origin-destination traffic flow rates between specific origin-destination nodes, the time period for which these rates are assumed to prevail, and the distribution of the vehicle types in the network.

The specified o-d rates are translated internally within the model into corresponding individual vehicle departures. Such departures are at uniform headways, at a rate corresponding to the specified departure rate, and only during the specified time frame window. Table 5 illustrates the file which contains the o-d rate information for the model. Several O-D rates can be specified for the same origin-destination set using separate or overlapping time periods. Any such departures are additive.

Table 5: QNET4: O-D Departure Rates by Time
(O-D Rates in each time interval)

FIRST LINE:
Numod: Number of origin-destination cells listed

ALL OTHER LINES:
Origin: Origin node for given O-D
Destination: Destination node for given O-D
ODrate: Departure rate for given O-D (veh/hr)
Starttim: Time at which given O-D flow rate starts (seconds)
Endtim: Time at which given O-D flow rate ends (seconds)
Krand: This is the fraction of the vehicle headway that is random
Probability 1: The fraction of vehicles that have no guidance
Probability 2: The fraction of vehicles that have complete guidance
Probability 3: The fraction of vehicles that have pre-planned routes

```
30
1, 2,  150,  0 , 3600 , 0, .4, .6,  0
1, 3,  150,  0 , 3600 , 0, .4, .6,  0
1, 4,  150,  0 , 3600 , 0, .4, .6,  0
1, 5,  150,  0 , 3600 , 0, .4, .6,  0
1, 6,  150,  0 , 3600 , 0, .4, .6,  0
1, 7,  150,  0 , 3600 , 0, .4, .6,  0
2, 1,  150,  0 , 3600 , 0, .4, .6,  0
2, 3,  150,  0 , 3600 , 0, .4, .6,  0
2, 4,  150,  0 , 3600 , 0, .4, .6,  0
2, 5,  150,  0 , 3600 , 0, .4, .6,  0
2, 6,  150,  0 , 3600 , 0, .4, .6,  0
2, 7,  150,  0 , 3600 , 0, .4, .6,  0
3, 1,  150,  0 , 3600 , 0, .4, .6,  0
3, 2,  150,  0 , 3600 , 0, .4, .6,  0
3, 4,  850,  0 , 3600 , 0, .4, .6,  0
3, 5,  150,  0 , 3600 , 0, .4, .6,  0
3, 6,  150,  0 , 3600 , 0, .4, .6,  0
3, 7,  150,  0 , 3600 , 0, .4, .6,  0
4, 1,  150,  0 , 3600 , 0, .4, .6,  0
4, 2,  150,  0 , 3600 , 0, .4, .6,  0
4, 3, 1800,  0 , 3600 , 0, .4, .6,  0
```

Table 6: QNET5.DAT Incident Descriptor File

```
  1
1020  1560   33   1.0

FIRST LINE:
Numinc:          Number of incidents to be evaluated

ALL OTHER LINES:
Incident Start:    Time at which the incident starts (seconds)
Incident End:      Time at which the incident ends (seconds)
Link Impacted:     Number of the link impacted by the incident
Lanes Affected:    Number of lanes affected by incident
```

e. QNET5: Incident or lane blockage descriptor file (start,end, location, severity)

Table 6 provides a description of the incidents which are intended to be modelled. The file indicates the incident start time, end time, the link impacted and the number of lanes affected. Several incidents are allowed for consideration at the same time on different links, or at different times on the same link. When the incident takes place it is modelled as occurring at the link's end, and the reduction in capacity is calculated in view of the effective number of lanes of traffic that are expected to be eliminated.

f.QNET6: Minimum Path Tree file (next node in path)

Table 7 illustrates the file used to communicate the minimum path trees to the program. The file is 7 columns wide, one for each zone, and the list is 44 lines long, one for each node in the network (lines 8 and 9 show all zeros, however, because there are no nodes 8 and 9). A zero indicates that there is no possible movement. Any other number indicates the link that is on the minimum path that leads to a specific destination zone. For example, if a vehicle heading for zone 7 were to be at node 10 one can see from the seventh column of the tenth line of table 6 that link 12 is the link that the vehicle will be taking next.

Table 7: QNET6.DAT Minimum Path Tree Find

0	10	10	10	10	10	10
25	0	25	25	25	25	25
67	67	0	67	67	67	67
32	32	32	0	32	32	32
14	14	14	14	0	14	14
18	18	18	18	18	0	18
22	22	22	22	22	22	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
1	12	12	26	12	12	12
9	35	35	35	5	16	35
11	19	44	44	11	6	19
53	24	53	53	53	17	7
20	2	62	20	20	20	20
29	33	33	29	33	33	33
8	8	8	8	8	8	8
4	4	4	4	4	4	4
28	30	30	30	30	30	30
27	34	34	34	34	34	34
41	41	41	41	41	41	41
38	42	42	38	42	42	42
13	13	13	13	13	13	13
31	31	31	31	31	31	31
37	37	37	39	37	37	37
36	43	43	36	36	43	43
50	50	50	50	50	50	50
47	51	51	47	47	47	51
15	15	15	15	15	15	15
40	40	40	40	40	40	40
48	46	46	48	48	46	46
45	52	52	45	45	45	52
59	59	59	59	59	59	59
56	60	60	56	56	56	56
21	21	21	21	21	21	21
49	49	49	49	49	49	49
57	55	55	57	57	57	55
54	54	61	54	54	54	54
68	68	68	68	68	68	68
65	69	69	65	65	65	65
23	23	23	23	23	23	23
58	58	58	58	58	58	58
66	64	66	66	66	66	66
70	63	70	70	70	70	70
3	3	3	3	3	3	3

EVERY LINE:

-- Each non-zero number indicates the next link on the minimum path to the destination zone.

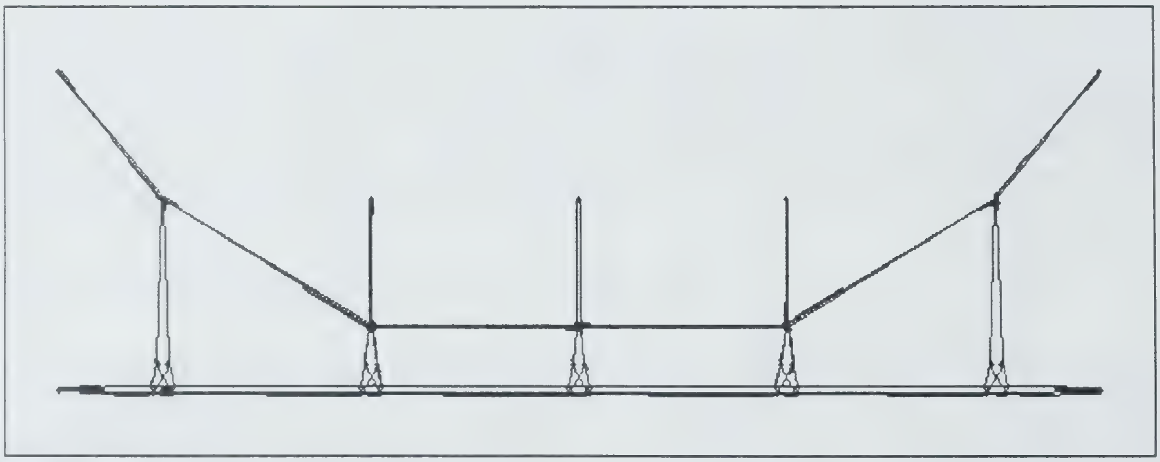
The file has as many columns as there are zones and as many rows as the highest node number used.

4. ILLUSTRATION OF TYPICAL MODEL OUTPUTS

For the user to be able to analyze and summarize the findings of a given simulation run, a series of output tables are generated during the run. The tables are such that the user can analyze the network on an individual level and/or system wide level. The output results are placed in the file identified by the batch file that ran the model. In this case, it is called RUN1.LST. In this output file, there are three types of tables which were produced at regular intervals as specified by the model. Examples of these tables and their descriptions follow.

FIGURE 2: Sample Screen Output

```
INTEGRATION VERSION 1.0           Dept. of Civil Eng. Queen's- R&D Branch MTO
                                Running File: run1.dat
Time:  1263.0 sec    21.0 min
DEPARTURE:  Time: 1262  Car:2414  Origin:  3  Dest:  1  Link:  67   Dept: 1333
ARRIVAL:    Time: 1263  Car:1883  Origin:  1  Dest   7  Start Time: 857
Building min. path trees:   7
Optimizing Signal Timings for :    5
 INCIDENT  1 LINK  33 TIME: 17.0 TO 26.0
```



FIRST LINE:	Program identification
SECOND LINE:	Present batch file that the model is simulating
THIRD LINE:	Time line showing present simulation time in seconds and minutes
FOURTH LINE:	Departures line which is updated at every departure in the network
FIFTH LINE:	Arrivals line which is updated at every arrival in the network
SIXTH LINE:	Path tree line which indicates when minimum path trees are recalculated
SEVENTH LINE:	Signal optimization line which indicates when the signal timings are being optimized
EIGHTH LINE:	Incident identification line which appears only when the incident is occurring in the network
THE GRAPHIC DISPLAY:	The graphic shows the network in blue, the traffic in green and red, the traffic signals in green and red and indicates where the inicdent occurs on the network with a red dot. Also displayed are the yellow squares of zone centroids and the yellow circles of the network nodes.

During run-time, various types of information can be sent to the screen as well as to the standard output files The initial set-up of the model does not have graphics output sent to the screen because the program execution speed is slowed down considerably by the graphics. However, information on the screen, including the graphics, can be toggled on and off, as may be desired by the user. An example of the full screen graphics output of the model is depicted in Figure 2.

a. Function Key Toggles for Screen Output

Below is a list of the active function keys and a short description of the function for each key. These keys can be activated at any time throughout the operation of the model. The purpose of these keys is to reduce or enhance the screen display of the model's output. The advantage of a reduced screen display is that the model's operation speed is increased. The advantage of enhancing the screen display is that the model can be observed as it progresses.

F1 Hold model's operation until F1 is pressed again
F2 Zoom
F3 Quit
F4 Turn time line on / off
F5 Turn departures and arrivals lines on and off
F6 Turn graphics on and off

b. User Oriented Travel Time Statistics

Table 8 is an origin-destination travel time matrix which contains the current travel times in seconds for each O-D zone pair. This table is generated every 15 minutes as specified by the model.

Table 8: Origin-Destination Travel Time Matrix (seconds)

ORIGIN DESTINATION TRIP TIMES IN MINUTES AFTER: 15.0 min

Origin	Destinations						
1	0.00	12.62	11.32	4.38	5.67	7.83	9.80
2	12.32	0.00	4.48	10.30	9.85	7.87	5.65
3	10.28	4.37	0.00	8.27	7.83	5.85	4.83
4	4.18	10.95	9.13	0.00	4.93	6.17	8.13
5	4.73	8.82	8.00	4.10	0.00	4.03	6.00
6	6.73	6.67	6.02	5.55	3.87	0.00	3.85
7	8.92	4.67	4.47	7.30	6.05	4.07	0.00

Table 9: Link Travel Time and Flow Statistics

LINK SUMMARIES AT TIME: 15 minutes run1.dat

	NODE Strt	NODE End	LINK Name	Typ	S P	Speed (kph)	Satur (vphg)	Ln (#)	Lgth (m)	Link Flow (vehs)	V/C ratio (#)	Total Time (min)	Aver Time (min)
1	10	1	TO-ZONE1	101	1	70.0	2000	2	1414	36	0.04	53	1.5
2	14	2	TO-ZONE2	101	1	70.0	2000	2	1414	37	0.04	53	1.4
3	44	3	TO-ZONE3	101	1	70.0	2000	2	900	253	0.25	282	1.1
4	17	4	TO-ZONE4	101	1	70.0	2000	2	900	180	0.18	188	1.0
5	11	5	TO-ZONE5	101	1	70.0	2000	2	1000	59	0.06	63	1.1
6	12	6	TO-ZONE6	101	1	70.0	2000	2	1000	71	0.07	76	1.1
7	13	7	TO-ZONE7	101	1	70.0	2000	2	1000	60	0.06	61	1.0
8	16	10	1ST AVENUE NB	1	2	50.0	1400	2	1300	26	0.04	50	1.9
9	11	10	KINGSTON RD WB	1	1	60.0	1600	1	2236	17	0.04	54	3.2
10	1	10	FR-ZONE1	1	1	70.0	2000	2	1414	181	0.18	292	1.6
11	12	11	KINGSTON RD WB	2	1	60.0	1600	1	2000	0	0.00	0	0.0
12	10	11	KINGSTON RD EB	2	1	60.0	1600	1	2236	108	0.26	372	3.4
13	22	11	2ND AVENUE NB	2	2	50.0	1400	1	300	75	0.22	117	1.6
14	5	11	FR-ZONE5	2	2	70.0	2000	2	1000	64	0.06	81	1.3
15	28	12	3RD AVENUE NB	3	2	50.0	1400	1	300	46	0.13	25	0.6
16	11	12	KINGSTON RD EB	3	1	60.0	1600	1	2000	17	0.04	39	2.3
17	13	12	KINGSTON RD WB	3	1	60.0	1600	1	2000	18	0.04	44	2.4
18	6	12	FR-ZONE6	3	2	70.0	2000	2	1000	63	0.06	68	1.1
19	12	13	KINGSTON RD EB	4	1	60.0	1600	1	2000	0	0.00	0	0.0
20	14	13	KINGSTON RD WB	4	1	60.0	1600	1	2236	118	0.29	401	3.4
21	34	13	4TH AVENUE NB	4	2	50.0	1400	1	300	67	0.19	76	1.1
22	7	13	FR-ZONE7	4	2	70.0	2000	2	1000	61	0.06	74	1.2
23	40	14	5TH AVENUE NB	5	2	50.0	1400	2	1300	28	0.04	55	1.9
24	13	14	KINGSTON RD WB	5	1	60.0	1600	1	2236	15	0.04	44	2.9
25	2	14	FR-ZONE2	5	1	70.0	2000	2	1414	180	0.18	293	1.6
26	10	15	1ST AVENUE SB	101	1	50.0	1400	2	1300	25	0.04	45	1.8
27	19	16	OFF RAMP QUEEN'S	101	1	50.0	1400	1	200	30	0.09	8	0.3
28	18	16	OFF RAMP QUEEN'S	101	1	50.0	1400	1	200	0	0.00	0	0.0
29	15	17	ON RAMP QUEEN'S	101	1	50.0	1400	1	200	25	0.07	7	0.3
30	18	17	QUEEN'S WAY WB	101	1	110.0	2000	2	200	180	0.18	25	0.1
31	23	18	QUEEN'S WAY WB1	101	1	110.0	2000	2	1800	181	0.18	233	1.3
32	4	19	FR-ZONE4	101	1	70.0	2000	4	900	543	0.24	557	1.0
33	15	20	ON RAMP QUEEN'S	101	1	50.0	1400	1	200	0	0.00	0	0.0
34	19	20	QUEEN'S WAY EB	101	1	110.0	2000	2	200	506	0.51	86	0.2
35	11	21	2ND AVENUE SB	101	1	50.0	1400	1	300	125	0.36	67	0.5
36	25	22	OFF RAMP QUEEN'S	101	1	50.0	1400	1	200	28	0.08	7	0.3
37	24	22	OFF RAMP QUEEN'S	101	1	50.0	1400	1	200	67	0.19	22	0.3
38	21	23	ON RAMP QUEEN'S	101	1	50.0	1400	1	200	32	0.09	8	0.3
39	24	23	QUEEN'S WAY WB	101	1	110.0	2000	2	200	174	0.17	25	0.1
40	29	24	QUEEN'S WAY WB2	101	1	110.0	2000	2	1800	249	0.25	341	1.4
41	20	25	QUEEN'S WAY EB1	101	1	110.0	2000	2	1800	444	0.44	660	1.5
42	21	26	ON RAMP QUEEN'S	101	1	50.0	1400	1	200	89	0.26	29	0.3
43	25	26	QUEEN'S WAY EB	101	1	110.0	2000	2	200	411	0.41	67	0.2
44	12	27	3RD AVENUE SB	101	1	50.0	1400	1	300	61	0.18	28	0.5
45	31	28	OFF RAMP QUEEN'S	101	1	50.0	1400	1	200	24	0.07	6	0.2
46	30	28	OFF RAMP QUEEN'S	101	1	50.0	1400	1	200	24	0.07	6	0.3
47	27	29	ON RAMP QUEEN'S	101	1	50.0	1400	1	200	32	0.09	8	0.3
48	30	29	QUEEN'S WAY WB	101	1	110.0	2000	2	200	256	0.26	39	0.2
49	35	30	QUEEN'S WAY WB3	101	1	110.0	2000	2	1800	287	0.29	399	1.4
50	26	31	QUEEN'S WAY EB2	101	1	110.0	2000	2	1800	428	0.43	652	1.5
51	27	32	ON RAMP QUEEN'S	101	1	50.0	1400	1	200	29	0.08	7	0.3
52	31	32	QUEEN'S WAY EB	101	1	110.0	2000	2	200	398	0.40	66	0.2
53	13	33	4TH AVENUE SB	101	1	50.0	1400	1	300	124	0.36	68	0.5
54	37	34	OFF RAMP QUEEN'S	101	1	50.0	1400	1	200	62	0.18	21	0.3
55	36	34	OFF RAMP QUEEN'S	101	1	50.0	1400	1	200	25	0.07	7	0.3
56	33	35	ON RAMP QUEEN'S	101	1	50.0	1400	1	200	91	0.26	30	0.3
57	36	35	QUEEN'S WAY WB	101	1	110.0	2000	2	200	239	0.24	34	0.1
58	41	36	QUEEN'S WAY WB4	101	1	110.0	2000	2	1800	269	0.27	355	1.3
59	32	37	QUEEN'S WAY EB3	101	1	110.0	2000	2	1800	357	0.36	535	1.5
60	33	38	ON RAMP QUEEN'S	101	1	50.0	1400	1	200	32	0.09	8	0.2
61	37	38	QUEEN'S WAY EB	101	1	110.0	2000	2	200	288	0.29	45	0.2
62	14	39	5TH AVENUE SB	101	1	50.0	1400	2	1300	24	0.03	42	1.7
63	43	40	OFF RAMP QUEEN'S	101	1	50.0	1400	1	200	0	0.00	0	0.0
64	42	40	OFF RAMP QUEEN'S	101	1	50.0	1400	1	200	32	0.09	8	0.3
65	39	41	ON RAMP QUEEN'S	101	1	50.0	1400	1	200	0	0.00	0	0.0
66	42	41	QUEEN'S WAY WB	101	1	110.0	2000	2	200	300	0.30	45	0.1
67	3	42	FR-ZONE3	101	1	70.0	2000	4	1150	334	0.15	408	1.2
68	38	43	QUEEN'S WAY EB4	101	1	110.0	2000	2	1800	273	0.27	380	1.4
69	39	44	ON RAMP QUEEN'S	101	1	50.0	1400	1	200	24	0.07	6	0.3
70	43	44	QUEEN'S WAY EB	101	1	110.0	2000	2	200	267	0.27	42	0.2

Total link travel times	=	8290 veh-mins
	=	138.16 veh-hrs
Total network travel	=	8396 veh-km
Total network length	=	59.85 km
Average network speed	=	61 km/h
Average trip time/veh	=	1.2102 min
Average trip length/veh	=	1.2257 km

c. System Oriented Link Statistics

Table 9 contains the statistics for each link in the network which describe their current status. This table is generated every 15 minutes, as specified by a parameter within the model, and indicates the flows, total travel time, average travel time and volume/capacity ratio.

d. Signal Timing Plan Summary

Table 10 contains the optimized signal timings for each signal in the network. The signal optimization and update occurs every **signalopt** seconds (see Table 4). This is a user determined variable placed in one of the input files.

Table 10: Optimized Signal Timing Plans

Timing Optimization at 15 mins for Signal 1

p	a	appr	flow	satf	yapr	ycri	ysum	cyc	L	grn	grn	igr	str	end
1	1	9	211	1600	0.13	0.23	0.38	30	8	22	13	4	0	13
1	2	10	936	4000	0.23	0.23	0.38	30	8	22	13	4	0	13
2	1	8	138	2800	0.05	0.15	0.38	30	8	22	9	4	17	26

Timing Optimization at 15 mins for Signal 2

p	a	appr	flow	satf	yapr	ycri	ysum	cyc	L	grn	grn	igr	str	end
1	1	11	0	1600	0.00	0.45	0.90	120	8	112	56	4	0	56
1	2	12	726	1600	0.45	0.45	0.90	120	8	112	56	4	0	56
2	1	13	628	1400	0.45	0.45	0.90	120	8	112	56	4	60	116
2	2	14	296	4000	0.07	0.45	0.90	120	8	112	56	4	60	116

Timing Optimization at 15 mins for Signal 3

p	a	appr	flow	satf	yapr	ycri	ysum	cyc	L	grn	grn	igr	str	end
1	1	16	118	1600	0.07	0.15	0.33	30	8	22	10	4	0	10
1	2	17	136	1600	0.09	0.15	0.33	30	8	22	10	4	0	10
2	1	15	250	1400	0.18	0.18	0.33	30	8	22	12	4	14	26
2	2	18	307	4000	0.08	0.18	0.33	30	8	22	12	4	14	26

Timing Optimization at 15 mins for Signal 4

p	a	appr	flow	satf	yapr	ycri	ysum	cyc	L	grn	grn	igr	str	end
1	1	19	0	1600	0.00	0.45	0.90	120	8	112	55	4	0	55
1	2	20	714	1600	0.45	0.45	0.90	120	8	112	55	4	0	55
2	1	21	638	1400	0.46	0.46	0.90	120	8	112	57	4	59	116
2	2	22	281	4000	0.07	0.46	0.90	120	8	112	57	4	59	116

Timing Optimization at 15 mins for Signal 5

p	a	appr	flow	satf	yapr	ycri	ysum	cyc	L	grn	grn	igr	str	end
1	1	24	171	1600	0.11	0.22	0.37	30	8	22	13	4	0	13
1	2	25	898	4000	0.22	0.22	0.37	30	8	22	13	4	0	13
2	1	23	153	2800	0.05	0.15	0.37	30	8	22	9	4	17	26

- p: Phase number for this link at the signal
- a: Number of the approach for the given phase.
- appr: Link number of this approach.
- flow: Estimate of the approach flow rate in veh/min.
- satf : Saturation flow rate for the approach in veh/min
- yapr : the flow ratio for the given approach
- ycri : the critical flow ratio for the phase
- ysum: the sum of all the critical flow ratios at the signal
- cyc : the cycle length in seconds
- L : the total lost time at the signal in seconds
- grn : the total green time at the signal in seconds
- grn : the green time for the given phase
- igr : the intergreen time for the given phase
- str : the start time within the cycle of the green phase
- end : the end time of the green within the phase

Table 11: Summary of Vehicle Journey Times

AVERAGE AND TOTAL O-D TRIP TIMES: run1.dat

Origin Zone	Dest. Zone	Number of Vehicles Depart	Arrival	Enroute	Average Trip Time (minutes)	Total Trip Time (minutes)
1	2	150	107	43	16.4	1750.5
1	3	150	116	34	12.9	1495.0
1	4	150	138	12	4.5	616.9
1	5	150	132	18	6.4	845.1
1	6	150	125	25	8.8	1093.8
1	7	150	115	35	13.4	1537.4
2	1	150	101	49	16.2	1637.0
2	3	150	136	14	4.6	630.1
2	4	150	117	33	12.1	1419.8
2	5	150	108	42	13.3	1432.2
2	6	150	128	22	8.9	1142.6
2	7	150	134	16	6.7	895.4
3	1	150	117	33	12.3	1437.7
3	2	150	138	12	4.5	621.1
3	4	850	719	131	8.4	6008.5
3	5	150	121	29	9.5	1149.4
3	6	150	136	14	5.9	806.0
3	7	150	112	38	6.9	773.1
4	1	150	139	11	4.3	600.9
4	2	150	118	32	13.0	1528.8
4	3	1800	1520	280	9.3	14153.1
4	5	150	132	18	6.1	799.4
4	6	150	132	18	6.2	822.2
4	7	150	122	28	9.9	1208.7
5	3	150	128	22	8.5	1090.3
5	4	150	139	11	4.4	615.1
6	3	150	135	15	6.3	851.5
6	4	150	135	15	5.7	766.7
7	3	150	136	14	4.8	651.1
7	4	150	126	24	7.7	963.8

Total demand to enter network = 6850
Vehicles entered network = 6850
Vehicles who completed trip = 5762
Vehicles left on network = 1088
Illegal network entries = 0

Computer time for Simulation Run =00:42:41

Sum of total trip time = 49343.1 mins 822.38 hrs
Average trip time = 8.56 mins 514 secs

e. Summary Statistics of Completed Trips

At the end of the simulation run, two other tables are generated. The first one summarizes the number of vehicles that completed their journey (as specified by an O - D), the average journey time for the arrivals and the total trip time. A summary of the vehicle demand on the network, the number of vehicles that entered and left the network and the number of vehicles left on the network after the simulation is also provided (see Table 11).

f. Incident Summary

Table 12 is a summary of any incidents that occurred in the network. However, if there were no incidents modelled, this table is not generated.

Table 12: Sumary of Incidents That Were Modelled

```
SUMMARY OF NETWORK INCIDENTS


INCIDENT  1 on link  33   from  15 to  20   1.0 lane reduction
  start time:  17.0 min   end time  :  26.0 min   duration  :  9.0 min
```

APPENDIX B:

AN INTEGRATED APPROACH TO MANAGING TRAFFIC CONGESTION IN COMBINED FREEWAY AND TRAFFIC SIGNAL NETWORKS

M. Van Aerde, J. Voss, A. Ugge and E.R. Case

ABSTRACT

In response to a need for a more comprehensive tool for dealing with traffic congestion in integrated freeway/traffic signal networks, a new simulation model called INTEGRATION-1 was developed. This paper first reviews the fundamental design of the model, prior to illustrating its various features for dealing with traffic congestion in complex networks. Subsequently, the capabilities of INTEGRATION-1 are illustrated using a sample model application to the QNET test network. This includes the analysis of a major freeway incident, the consequent queueing and rerouting of traffic, and the generation of real-time changes in signal timings along the affected parallel arterial. The paper concludes with a description of the on-going development and testing of INTEGRATION-1 and other related models.

1. INTRODUCTION

The past two decades have seen tremendous advances in the development and application of computerized tools for dealing with a wide variety of traffic signal and freeway control problems. For example, programs for optimizing isolated traffic signals (HCM Software(1) and MICRO- SINTRAL(2)), coordinated arterials (PASSER(3)) or signalized area networks (TRANSYT(4)) have been successfully applied to generate efficient fixed-time signal timing plans, while SCOOT(5) has made practical real-time traffic signal control possible. Similarly, models for freeways (INTRAS(6) and FRECON(7)) and freeway corridors (FREQ(8) and CORQ(9)) have resulted in improved freeway control strategies.

a. The New Type of Traffic Control Problem

However, while the above traffic control tools were being developed to deal primarily with undersaturated conditions, traffic congestion in large metropolitan areas increased rapidly and spread sufficiently to present a new generation of oversaturation traffic control problems. The growing traffic congestion has increased both the scope and scale of the control problem, while simultaneously constraining the range of alternative solutions that are available or applicable(10).

At first, increased freeway congestion causes parallel arterials to also become congested, such that the number of alternate diversion routes quickly diminishes. Later, this lack of diversion opportunities results in much more frequent and larger freeway queues, while on the parallel arterials more advanced signal optimization/coordination algorithms are required to deal with oversaturated traffic signals. Finally, as congestion spreads spatially, congestion management becomes a multi-directional network control problem as opposed to simply a directional corridor control problem(10).

b. Integrated Networks and Their Control

Clearly, none of the earlier traffic models were designed to deal with such a dramatic range of diverse and acute traffic problems. Some techniques could address one specific aspect of the problem, but were unable to estimate the larger network-wide implications in view of the various other control strategies that were in effect. What appeared to be lacking was a single comprehensive model for dealing simultaneously with all aspects of integrated traffic signal/freeway networks during periods of extreme congestion. In addition, such a model should not only consider current control strategies, but also incorporate recent advances in on-board driver information systems.

Although the need for integrated networks and integrated control strategies has been established for some time, solutions to this problem have been difficult to obtain for a variety of technical and non- technical reasons(11). The primary reason derives from the difficulty in simultaneously modelling freeways and traffic signals, real- and fixed-time control, and queueing and traffic assignment within a single simulation/optimization model(10). However, based on a review of the most relevant traffic models developed to date(12), the design of a model which can deal specifically with integrated networks was formulated(13). The resulting

model(14), which is called INTEGRATION-1, is currently being tested and validated at Queen's University in Kingston, Canada, under the sponsorship of the R&D Branch of the Ministry of Transportation of Ontario(15). As the background to the model's development is described elsewhere(13,14), this paper provides an overview of the modelling approach of INTEGRATION-1 and concentrates on discussing and illustrating its features for dealing with traffic congestion problems using a typical model simulation run.

2. INTEGRATION-1 MODELLING APPROACH

INTEGRATION-1 consists of a discrete simulation in which each vehicle's path is traced throughout the network. The links which a vehicle utilizes are selected in accordance to its estimate of the "best route" (from its origin to its destination), and along its path each vehicle's route is further adjusted in view of any changes in the prevailing traffic congestion and/or the traffic controls.

a. Modelling of Traffic Flow and Controls

Along its route each vehicle is always delayed an amount of time equal to the link's uncongested travel time. In addition, each vehicle may be further delayed if it encounters traffic queues, traffic signals, ramp meters or incidents which cause lane blockages. Periodically, new estimates of the minimum path routes are derived in view of updated measurements of the prevailing traffic conditions, such that the minimum path routing of any affected drivers can be automatically updated.

Any traffic controls are modelled as time-dependent controls on the exit privileges from each affected network link. For example, if a given link is controlled by a traffic signal, exit privileges will be denied during the red phase of each cycle, while any accumulated queues can subsequently discharge during the green phase at the applicable saturation flow rate. Similarly, any ramp metering strategies are modelled as traffic signals with appropriate cycle times to produce the desired ramp metering rate. In all cases, the signal timings and/or ramp metering rates can be set in isolation, can be coordinated or they can be optimized by routines external to the INTEGRATION model.

c. Modelling of Incidents and Congestion

Incidents are modelled as reductions in the number of available lanes. Such reductions can be for any pre-specified duration in minutes and any valid number or fraction of lanes. Consequently, even incidents removed to the shoulder can be modelled as a loss of an equivalent fraction of a lane. In addition to the primary impact of a reduction in the number of lanes, there may also be a secondary impact in the form of a reduction in saturation flow per lane when a queue develops. For example, an incident which reduces the number of lanes from 3 to 2 may result in an initial capacity reduction from 6000 to 4000 pcph (passenger cars per hour) (2 lanes x 2000 pcph/lane), but may at the onset of queueing produce a further capacity reduction to 3000 pcph (2 lanes x 1500 pcph) if the saturation flow per lane is known to drop from 2000 to 1500 pcph during congested conditions.

INTEGRATION-1 reflects the most important attributes of congestion through its explicit account of queue growth/decay, while maintaining a dynamic equilibrium traffic assignment. The explicit account of queue size and delay through the tracing of individual vehicles permits direct modelling of queue-spill back from upstream links, continuous modelling of traffic signal progression even though one or more intersections are oversaturated, and automatic delay of downstream link arrivals if they are held up at an upstream bottleneck. In addition, as the relative travel time between the shorter (but congested) route, and a longer (but less congested) route changes, new arrivals will automatically redistribute themselves to avoid the congested link or area.

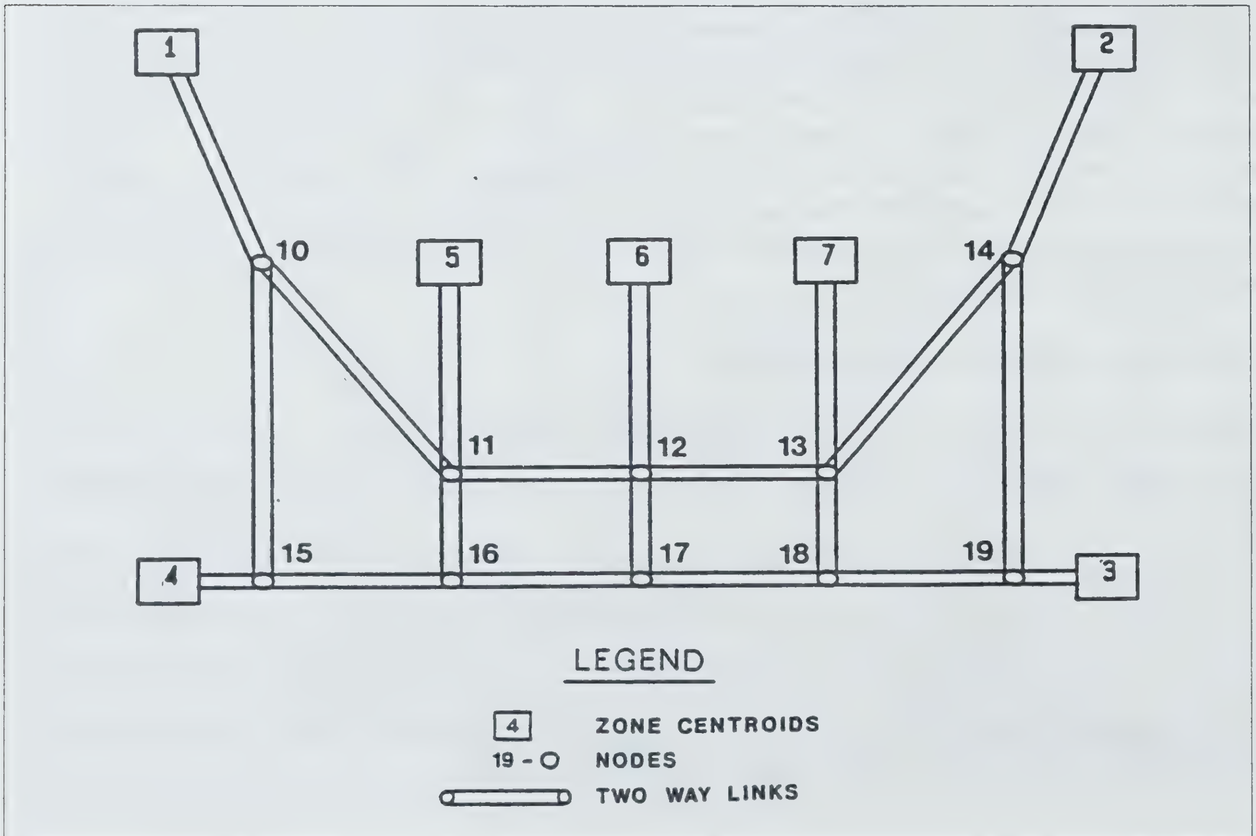
3. ILLUSTRATION OF AN INTEGRATION-1 SAMPLE SIMULATION RUN

The properties of the INTEGRATION-1 simulation model are illustrated in this section using the input data and results of a sample model run.

a. Network and Traffic Control Representation

A sample model application is illustrated in this paper for a network consisting of a 4-lane freeway, a parallel signalized arterial, and a variety of cross-streets which join the freeway to the arterial and the trip origins/destination zones. The relatively small test network, which contains 7 zones, 10 pure nodes and 40 directional links, is illustrated in Figure 1.

Figure 1: Network Configuration of Sample QNET Test Network



The configuration of the traffic network is described to the model in terms of the node/zone coordinates, a reference to the start/end node/zone of each link, plus a listing of each link's free-speed, saturation flow rate per lane, and the effective number of lanes in each direction. In addition, the characteristics of a link are further specified with reference to the number and phase of the link's traffic signal.

The operation of each traffic signal is specified in terms of its cycle length, effective green phase start/end times, and the relative offset of phase 1 to the master clock, as illustrated in Table 1. In this way all (or some) of the signals can be coordinated on a common cycle or they can each operate on their own as isolated signals. The signal timing plans that are utilized in the model can either be externally specified to simulate fixed-time control, or can be dynamically re- calculated internally to model the effect of real-time control in a "SCOOT-like" fashion.

b. Traffic Demand Representation and Routing

Traffic demands are specified as origin-destination flow rates for given time periods. The model internally translates these flow rates into corresponding individual vehicle departures during the time period that is specified. In this fashion traffic demands can be expressed to produce any desirable type of traffic demand pattern variation, such as a constant background demand which prevails for 15 to 60 minutes at a time, plus any short traffic peaks lasting for only a few minutes. Such shorter peaks may be generated by, for example, employees leaving from a manufacturing plant at the end of a shift, or spectators leaving a sports stadium at the end of a game. Of course, the simulation model does not care about how the information on

Table 1: Typical Example of QNET Signal Timing Plan

```
5
1   60   0   2   0  41   4  45  56   4
2   60   0   2   0  41   4  45  56   4
3   60   0   2   0  41   4  45  56   4
4   60   0   2   0  41   4  45  56   4
5   60   0   2   0  41   4  45  56   4
```

FIRST LINE:

Numsignals:	The number of signals listed.

ALL OTHER LINES:

Signal number:	The number of the signal (referred to in QNET2.DAT)
Cycle Time:	The duration of the cycle time (seconds)
Offset Time:	The relative offset of phase(i) with respect to phase 1 of signal 1 (seconds)
Number of Phases:	Number of phases at the signal
Phase start:	Start time of phase(i) (seconds)
Phase end:	End time of phase(i) (seconds)
Lost time:	Lost time of phase(i) (seconds)

these departure patterns are derived, as its operation deals only in terms of individual vehicles which have a specific origin, departure time and desired destination.

Vehicles are routed through the network based on the destination- specific turning movements that are provided at the end of each network link. These turning movements are virtually continuously re-calculated for all destinations using a tree building algorithm and the most current estimates of link travel times, as illustrated in Figure 2. The minimum paths consider the prevailing link speeds, any queues on freeways or at traffic signals, and any spillback from downstream links. In addition to the dynamic minimum path trees, which are calculated based on perfect knowledge of current traffic conditions, a separate set of static trees can be made available. These may provide routings to a certain subset of the drivers based only on historical (as opposed to real-time) travel time estimates. Consequently, the behaviour of a mix of drivers with varying knowledge of current vs. historic traffic conditions can be modelled explicitly.

c. Simulation Results and Outputs

During the simulation the model provides a real-time graphical illustration of the performance of the traffic network, which indicates the amount of traffic and queueing on each network link, in addition to the status of any traffic signals. A typical sequence of traffic signal timings during a simulation period with a freeway incident is illustrated in Figure 3.

Ten times every minute new dynamic routings to each destination are re- calculated and every 5 minutes a new set of signal timings can be calculated based on the current traffic flow conditions on each link. This signal timing recalculation selects a new optimum cycle time and/or reallocates the green phase times while maintaining a set of pre- specified reference offsets. The results of such a sample optimization were illustrated in Figure 3, which contains the timings produced for an incident on link 33 (from node 16 to 17). Due to the magnitude of the differences in optimum cycle times, each intersection was allowed to operate under critical intersection control as an isolated intersection, as opposed to being coordinated at a common cycle length.

At the conclusion of the simulation run the model produces two types of summary outputs. The first provides user-oriented statistics on the trips between each origin-destination, as illustrated in Table 2, while the second provides system-oriented statistics on the operation of each network link, as shown in Table 3. The origin-destination data indicates what type of trips are most adversely affected by a certain traffic management strategy, while the link data can indicate any shifts in traffic flow patterns through the network or may identify particular network bottlenecks.

Figure 2: Dynamic Minimum Path Tree towards a Specific Destination

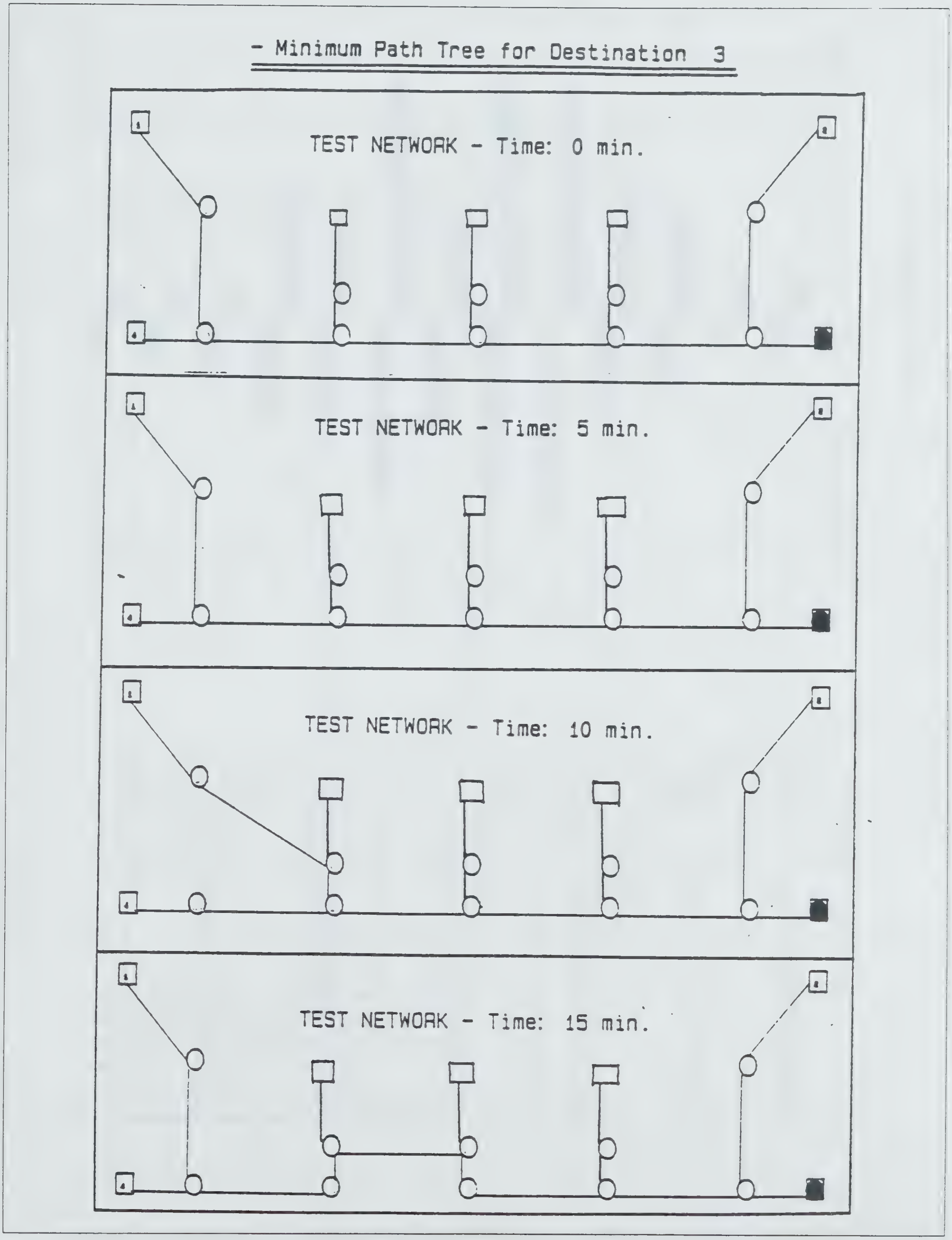
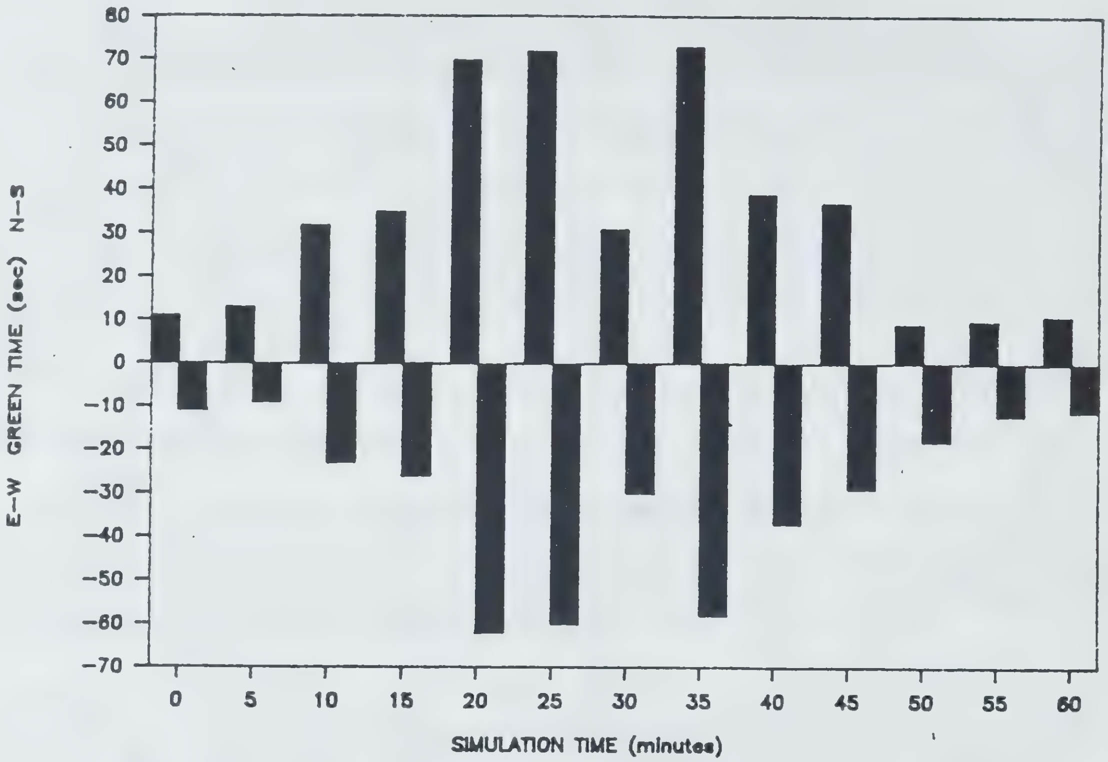


Figure 3: Real-Time Changes in Signal Timing Plan During Incident



Time (min)	Cycle Length (sec)	Phase 1		Phase 2	
		Green Time (sec)	Percent of Cycle Length	Green Time (sec)	Percent of Cycle Length
0	30	11	37	11	37
5	30	13	43	9	30
10	63	32	51	23	37
15	69	35	51	26	38
20	140	70	50	62	44
25	140	72	51	60	43
30	69	31	45	30	43
35	139	73	53	58	42
40	84	39	46	37	44
45	74	37	50	29	39
50	35	9	26	18	51
55	30	10	33	12	40
60	30	11	37	11	37

Table 2: User Oriented Summary Statistics from INTEGRATION Model

TRIP TIME FOR EACH VEHICLE UNDER SIMULATED CONDITIONS

Origin Zone	Dest. Zone	Number of Arrivals	Average Trip Time (minutes)	Total Trip Time (minutes)
1	2	150	14.8	2222.3
1	3	150	12.6	1890.7
1	4	150	4.9	738.6
1	5	150	6.4	951.8
1	6	150	9.1	1369.6
1	7	150	11.9	1781.7
2	1	150	14.0	2103.4
2	3	150	5.1	764.4
2	4	150	11.4	1712.0
2	5	150	11.1	1664.9
2	6	150	8.6	1286.4
2	7	150	6.1	910.6
3	1	150	11.3	1701.2
3	2	150	4.7	697.9
3	4	675	8.8	5915.6
3	5	150	8.5	1266.3
3	6	150	6.3	944.5
3	7	150	5.2	774.6
4	1	150	4.8	712.1
4	2	150	12.3	1846.3
4	3	1350	9.8	13229.4
5	3	150	8.8	1317.9
5	4	150	4.7	701.7
6	3	150	6.7	998.7
6	4	150	6.2	931.7
7	3	150	5.0	745.2
7	4	150	7.9	1185.5

Sum of total trip time = 50364.6 mins 839.41 hrs

Total demand to enter network= 5775
Vehicles entered network = 5775
Vehicles who completed trip = 5775
Vehicles left on network = 0

Computer time for Simulation Rum =00:31:50

Table 3: System Oriented Summary Statistics from INTEGRATION Model

LINK SUMMARIES AT TIME: 10 minutes

LINK Num	Name	Typ S	P	Speed (kph)	Satur (vphg)	Ln (#)	Lgth (m)	Node from (#)	to (#)	Link Flow (vehs)	V/C ratio (#)	Total Time (min)	Aver Time (min)
1	TO-ZONE1	101	1	70.0	2000	2	1414	10	1	17	0.03	27	1.6
2	TO-ZONE2	101	1	70.0	2000	2	1414	14	2	17	0.03	27	1.6
3	TO-ZONE3	101	1	70.0	2000	2	1000	19	3	108	0.16	130	1.2
4	TO-ZONE4	101	1	70.0	2000	2	1000	15	4	82	0.12	101	1.2
5	TO-ZONE5	101	1	70.0	2000	2	1000	11	5	20	0.03	24	1.2
6	TO-ZONE6	101	1	70.0	2000	2	1000	12	6	21	0.03	28	1.4
7	TO-ZONE7	101	1	70.0	2000	2	1000	13	7	27	0.04	30	1.1
8	FR-ZONE1	1	1	70.0	2000	2	1414	1	10	144	0.22	253	1.8
9	KINGSTON RD WB	1	1	60.0	1600	1	2236	11	10	4	0.01	16	4.0
10	1ST AVENUE NB	1	2	50.0	1400	2	1500	15	10	19	0.04	46	2.4
11	FR-ZONE5	2	2	70.0	2000	2	1000	5	11	54	0.08	62	1.1
12	KINGSTON RD EB	2	1	60.0	1600	1	2236	10	11	45	0.16	163	3.6
13	KINGSTON RD WB	2	1	60.0	1600	1	2000	12	11	0	0.00	0	0.0
14	2ND AVENUE NB	2	2	50.0	1400	1	500	16	11	25	0.11	30	1.2
15	FR-ZONE6	3	2	70.0	2000	2	1000	6	12	54	0.08	61	1.1
16	KINGSTON RD EB	3	1	60.0	1600	1	2000	11	12	10	0.04	26	2.6
17	KINGSTON RD WB	3	1	60.0	1600	1	2000	13	12	9	0.03	23	2.6
18	3RD AVENUE NB	3	2	50.0	1400	1	500	17	12	14	0.06	13	0.9
19	FR-ZONE7	4	2	70.0	2000	2	1000	7	13	54	0.08	62	1.1
20	KINGSTON RD EB	4	1	60.0	1600	1	2000	12	13	0	0.00	4	0.0
21	KINGSTON RD WB	4	1	60.0	1600	1	2236	14	13	42	0.15	149	3.5
22	4TH AVENUE NB	4	2	50.0	1400	1	500	18	13	30	0.13	36	1.2
23	FR-ZONE2	5	1	70.0	2000	2	1414	2	14	144	0.22	253	1.8
24	KINGSTON RD WB	5	1	60.0	1600	1	2236	13	14	4	0.01	14	3.4
25	5TH AVENUE NB	5	2	50.0	1400	2	1500	19	14	20	0.04	45	2.3
26	FR-ZONE4	101	1	70.0	2000	2	1000	4	15	284	0.43	359	1.3
27	1ST AVENUE SB	101	1	50.0	1400	2	1500	10	15	43	0.09	99	2.3
28	QUEEN'S WAY WB1	101	1	110.0	2000	2	2000	16	15	89	0.13	136	1.5
29	2ND AVENUE SB	101	1	50.0	1400	1	500	11	16	56	0.24	49	0.9
30	QUEEN'S WAY EB1	101	1	110.0	2000	2	2000	15	16	229	0.34	365	1.6
31	QUEEN'S WAY WB2	101	1	110.0	2000	2	2000	17	16	129	0.19	206	1.6
32	3RD AVENUE SB	101	1	50.0	1400	1	500	12	17	46	0.20	39	0.8
33	QUEEN'S WAY EB2	101	1	110.0	2000	2	2000	16	17	201	0.30	331	1.6
34	QUEEN'S WAY WB3	101	1	110.0	2000	2	2000	18	17	167	0.25	268	1.6
35	4TH AVENUE SB	101	1	50.0	1400	1	500	13	18	59	0.26	50	0.8
36	QUEEN'S WAY EB3	101	1	110.0	2000	2	2000	17	18	163	0.24	268	1.6
37	QUEEN'S WAY WB4	101	1	110.0	2000	2	2000	19	18	203	0.30	320	1.6
38	FR-ZONE3	101	1	70.0	2000	2	1000	3	19	247	0.37	304	1.2
39	5TH AVENUE SB	101	1	50.0	1400	2	1500	14	19	49	0.11	110	2.2
40	QUEEN'S WAY EB4	101	1	110.0	2000	2	2000	18	19	121	0.18	190	1.6

4. DISCUSSION OF CASE STUDY APPLICATION AND OTHER ADVANCED FEATURES

During the development and testing of the above case study, a number of related applications for the INTEGRATION-1 model were developed in parallel. These spin-off applications and their potential to assist in improved traffic congestion management is briefly discussed below.

a. Incident Management Plan Development

The important application of INTEGRATION-1 is likely to be its use as an off-line tool for developing incident management plans in congested networks. In its current format, a range of typical incidents can first be pre-evaluated using the model and iteratively developed into a library of mitigating strategies. Subsequently, one of these validated strategies can then be quickly implemented, either automatically or through operator intervention, when a matching or similar incident actually occurs later on. Through such off-line development of incident management plans, the plan's consequences on freeway operations and increased congestion on any parallel arterials can be pre- determined. This would limit the chance that any negative impacts could develop that would perhaps be unforeseen initially if the strategy had not first been simulated . Also, these incident response plans can be refined off-line to an extent that would be impossible using on-line experimentation alone.

b. Evaluation of Fixed-Time and Real-Time Signal Control Strategies

It is often a difficult decision to determine if intersections with different optimum cycle times should be coordinated during congested conditions, in order to maintain signal progression, or if the most critical intersections should be operated separately at a longer cycle length, in order to yield a higher ultimate throughput capacity.

The capabilities of INTEGRATION-1 to model a mixture of coordinated and uncoordinated intersections during congested conditions allows one to directly consider such trade-offs. Furthermore, when the coordination option is selected, the INTEGRATION-1 can still be used to model the effects of queue spill back to upstream intersections, and can model any queue holdback effects when the capacity of one intersection limits or constrains the arrival rate at subsequent downstream intersections.

In terms of the evaluation of real-time signal control strategies, the model is being used as a direct test-bed for analyzing the impacts of a variety of control parameters and for estimating the overall effectiveness of real-time control. Relatively simple parametric studies can be performed on each critical variable while the performance of each strategy can be compared using a consistent and unbiased evaluator.

c. Evaluation of Alternative Driver Information Systems

The model's direct accounting of the routing behaviour of individual vehicles within an integrated freeway/traffic signal network provides considerable opportunities for testing and evaluating alternative driver information systems. Specifically, as the model can consider a

mixture of drivers which each have access to different routing information sources, the effect of providing some drivers with improved routing information (ie vehicles equiped with on-board route guidance systems) can be examined against a background of drivers which only have access to historical traffic information data. In addition, the impact of the provision of selective data to particular destinations or along certain routes can be examined by limiting the access to improved data to either certain users or specific parts of the network(16).

CONCLUSIONS

The unique features of INTEGRATION-1, which allow it to accurately model congested freeways and signalized streets in a single integrated fashion, permit valuable insights into a number issues associated with the operation of congested traffic networks. Not only does the model allow a more detailed examination of certain strategies in isolation, such as critical intersection control, real-time control, or improved driver information systems, but it also allows the often complex interactions to be studied simultaneously.

INTEGRATION-1 is at present only available as a research tool and requires significant further development. This development is currently being carried out at the Department of Civil Engineering, Queen's University, Kingston, in cooperation with the Research and Development Branch of the Ministry of Transporation of Ontario, Downsview, Canada. Some of these developments include the coding of a more refined real- time control algorithm(15), the design of a compatible data input pre- processor which generates synthetic O-D's from link counts(17), and a direct interface to a comprehensive driver information system(18,19). Each of the above options is currently being tested using data for the Burlington Skyway FTMS on the QEW near Hamilton, Ontario(20).

When the model and its support routines are complete, they will not only provide a valuable operational and research tool, but also a very graphic educational environment within which new traffic engineers can learn more about a variety of traffic congestion issues, problems and solutions.

REFERENCES

1. Federal Highway Administration (1987), Highway Capacity Software - User's Manual, U.S. Department of Transportation, Washington,D.C.

2.Stephenson,B. and Teply,S. (1985), Micro-Sintral - User Manual, Institute of Transportation Engineers, District 7 - Canada.

3.Texas State Department of Highways and Public Transportation(1980), PASSERII-80 User's Manual.

4.Federal Highway Administration (1987), Transyt-7F User's Manual, U.S. Department of Transportation and University of Florida, Gainesville.

5.Hunt,P.B., Robertson,D.I., Bretherton,R.D. and Winton,R.I.(1981), SCOOT - A Traffic Responsive Method of Coordinating Signals, TRRL LR 1014, Crowthorne, Berkshire.

6.Wicks,D.A.(1977), INTRAS- A Microscopic Corridor Simulation Model, Overview of Simulation in Highway Transportation, Vol 1, pp. 95-107.

7. Campbell,J.F. et al (1984), FRECON2 User's Guide, ITS, UC Berkeley, (UCB-ITS-TR-84).

8. May,A.D.(1984), Traffic Management Research at the University of California, Schriftenreihe des Instituts fur Verkehrswesen des Universitat Karlsruhe.

9. Yagar,S.(1975), CORQ - A Model for Predicting Flows and Queues in a Road Corridor, Transportation Research Record 533, pp. 77-87.

10. Van Aerde,M.(1985), Modelling of Traffic Flows, Assignment and Queueing in Integrated Freeway/Traffic Signal Networks, Ph.D. Dissertation, University of Waterloo, Canada.

11.Yagar,S. Ed. (1983), Traffic Monitoring and Control Systems, Proceedings, Engineering Foundation Conference, Henniker, New Hampshire.

12.Van Aerde,M., Yagar,S., Ugge,A. and Case,E.R.(1988), A Review of Candidate Freeway/Arterial Corridor Traffic Models, Transportation Research Record 1132, Washington D.C., pp. 53-65.

13. Van Aerde,M. and Yagar,S.(1988a), Dynamic Integrated Freeway/Traffic Signal Networks: Problems and Proposed Solutions, Transportation Research A, Pergamon Press.

14. Van Aerde,M. and Yagar,S.(1988b), Dynamic Integrated Freeway/Traffic Signal Networks: A Routing-Based Modelling Approach, Transportation Research A, Pergamon Press.

15. Van Aerde,M. and Voss,J.(1988), Integration-1 User's Manual, Prepared at Dept. of Civil Eng., Queen's University for Ministry of Transportation, Ontario

16. Van Aerde,M. and Case,E.R.(1988), Individual driver route guidance systems and their implications for Traffic Control, Canadian Journal of Civil Engineering, Volume 15, Number 2.

17. Van Aerde,M., Voss,J. and Noxon,G.(1988), On-Line Generation of Synthetic Origin-Destination Counts for Application in Freeway Corridor Traffic Control, Submitted for Presentation at 1989 Annual Meeting of Transportation Research Board, Washington, D.C.

18. Van Aerde,M. and Blum,Y.(1988), Electronic Driver Route Guidance in Congested Networks, ITE Journal, Volume 58, Number 8, pp. 33-37.

19. Blum.Y, and Van Aerde,M.(1988), Traffic Responsive Approach to In- Vehicle Route Guidance using Q-Route, Submitted for Presentation at 1989 Annual Meeting of Transportation Research Board, Washington, D.C.

20. Van Aerde,M., J.Voss, Y.Blum, A. Ugge and E.R. Case (1989), Modelling the Burlington Skyway FTMS During Recurring and Non- Recurring Congestion, Engineering Foundation Conference on Traffic Control Methods, Santa Barbara.

APPENDIX C:

ON-LINE GENERATION OF SYNTHETIC ORIGIN-DESTINATION COUNTS FOR APPLICATION IN FREEWAY CORRIDOR TRAFFIC CONTROL

M. Van Aerde, J. Voss and G. Noxon

ABSTRACT

A need exists during the application of freeway corridor control models to determine the prevailing O-D matrices for each time-slice during the peak period to be analyzed. As it is virtually impossible to obtain these matrices directly by survey, a fully automated approach is proposed which employs Freeway Traffic Management System (FTMS) data already being collected. This approach relies on existing algorithms for formulating synthetic O-D counts from observed link flows, but employs a special relationship that exists between O-D matrices for consecutive time-slices to carry out these computations more efficiently and often also with greater accuracy.

This paper first describes the general background to the problem and the general solution approach that has been proposed. Subsequently, several different analysis runs using the proposed approach are described which were performed using data for the Burlington Skyway FTMS in Ontario. The results of these runs illustrate the details of the technique and demonstrate the main reasons for the improved efficiencies and accuracy. The paper is concluded with a discussion of how the procedure can be further refined and implemented in both its off-line and on-line modes within existing FTMS installations.

1. INTRODUCTION

a. Background

During the past decade a number of techniques were developed for estimating synthetic origin-destination (O-D) demands from observed link flow counts. Such techniques proved to be efficient and cost-effective in generating the demand data required for transportation planning studies, when either direct survey methods were impractical or too expensive. In freeway corridor problems, all assignment-based control models require that the traffic demands are also expressed as origin- destination flow rates for the freeway corridor (Van Aerde et al.,1987). However, because of the operational rather than planning character of the analysis, a sequence of O-D matrices is required to express the changes in traffic demand during the peak period that is analyzed. Consequently, a number of O-D matrices must be derived, rather than just one single matrix.

b. Objectives of the Paper

Such a sequence of O-D data is difficult and expensive to obtain for use with off-line simulation models. Furthermore, at present it is virtually impossible to obtain such O-D's on-line for use with real-time traffic control or diversion models. This paper proposes a technique which can efficiently generate this sequence of O-D matrices on-line using real-time data. The technique is based on a special relationship that exists between O-D matrices for consecutive time-slices. The objective of the paper is to demonstrate the feasibility of the technique, to illustrate its results and limitations, and to outline how the technique could be used in practice.

2. PROCEDURE FOR GENERATING AN O-D MATRIX FOR ONE TIME-SLICE

The procedure for generating synthetic O-D's was developed based on an existing algorithm by Van Zuylen and Willumsen (1980).

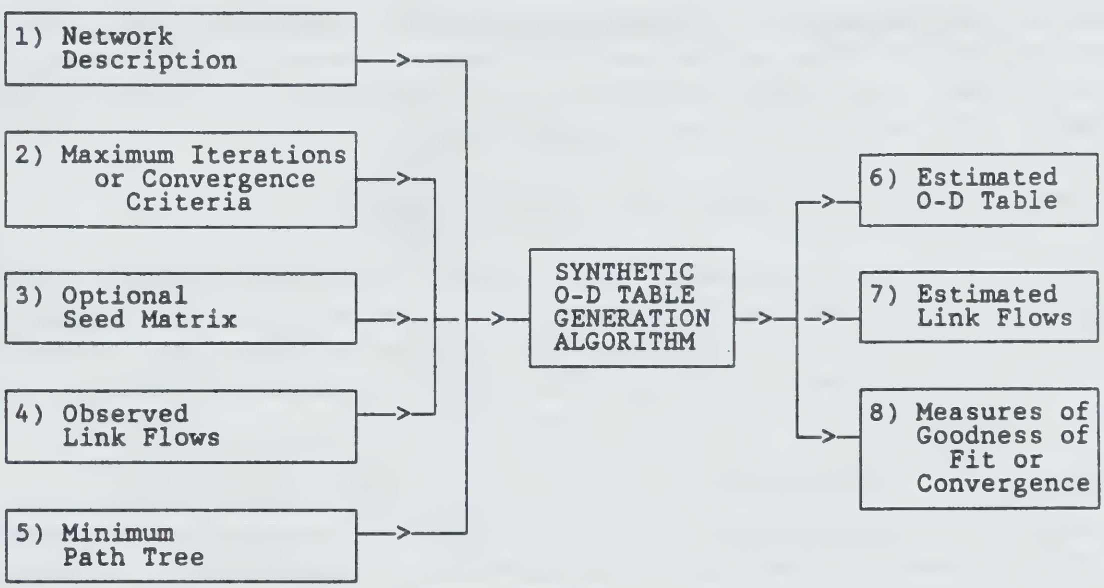
a. Synthetic O-D's in Transportation Planning

Many techniques exist for developing synthetic O-D data from link flows. Examples of these, which have been applied in a transportation planning context, include a Generalized Least Squares Estimator (Cascetta, 1984), Bayesian Statistical Approach (Maher, 1983), Constrained Regression (Hendrickson et al., 1984) and Information Minimization - Entropy Maximization (Van Zuylen and Willumsen, 1980; Van Zuylen, 1981).

The general procedure involved in applying these methods is illustrated in Figure 1. As shown, the inputs to the analysis consist of a network description file, a set of convergence criteria, a series of minimum path trees, a list of observed link flows and an optional seed matrix. Within the analysis, the minimum path trees are utilized to determine which origin-destination pairs contribute to which link flows, and with the simpler algorithms only one path is allowed between each O-D pair. As there are many more variables than constraints to this problem, there are numerous different mathematical solutions possible. The derivation of a mathematical solution which closely matches the "correct" matrix is therefore assisted considerably if the

Figure 1: Basic Procedure for Genrating Synthetic O-D's

INPUT REQUIREMENTS: **OUTPUT:**



1. Network Description: link/node structure of the network
2. Convergence Criteria: a criterion used to terminate the algorithm
3. Optional Seed Matrix: old or approximate matrix to initiate search
4. Observed Link Flows: link traffic flows actually measured
5. Minimum Path Tree: listing of links on most efficient routes
6. Estimated O-D Matrix: O-D flows estimated by algorithm
7. Estimate Link Flows: link flow counts estimated by algorithm
8. Measures of Convergence: indicators of the algorithms convergence

could be automatically generated by Integration, while the O-D table generated by SODGE could be input directly into Integration. Figure 6.3 illustrates the input requirements of SODGE and its compatability with Integration.

algorithm is provided with a priori knowledge of the general travel pattern structure in the form of a seed matrix. This seed matrix is utilized to initiate the solution search and reduces the number of required algorithm iterations. As it will also impart its general structure onto the final solution matrix, it consistently results in a much improved final O-D matrix estimate.

The quality of the generated matrix is ideally determined by measuring the deviation between the predicted O-D cell values and the actual O-D counts. However, as the technique is intended to be used when actual O-D counts are not available, the next best quality indicator is the ability of the matrix to reproduce the original link flows.

b. Selection of a Suitable Method to Generate an O-D Matrix

Of the available synthetic O-D techniques, the Information Minimization- Entropy Maximization algorithm by Van Zuylen and Willumsen (1980), and revised by Van Zuylen (1981), was considered most suitable for the intended use. The principles and steps of this algorithm are well- documented, and a version of the algorithm implemented in the ME2 model has been satisfactorily validated by Van Vliet and Willumsen (1981).

The above algorithm determines the most likely O-D matrix by solving for that matrix which minimizes the information contained in the final O-D matrix. The actual solution algorithm is derived by formulating a linear equation which considers each link flow to be a result of a series of trips between all O-D pairs which have routes utilizing that particular link. For O-D cells which utilize multiple paths, the appropriate proportions utilizing the link along each path are expressed as probabilistic fractions. In the case of an "all-or-nothing" assignment, these probabilities end up being either zero or one, depending on whether a given link was utilized or not. The entire problem formulation is then a series of linear equations, including an objective function which maximizes the entropy measure of the trip matrix, and a number of constraints arising from the observed link volumes.

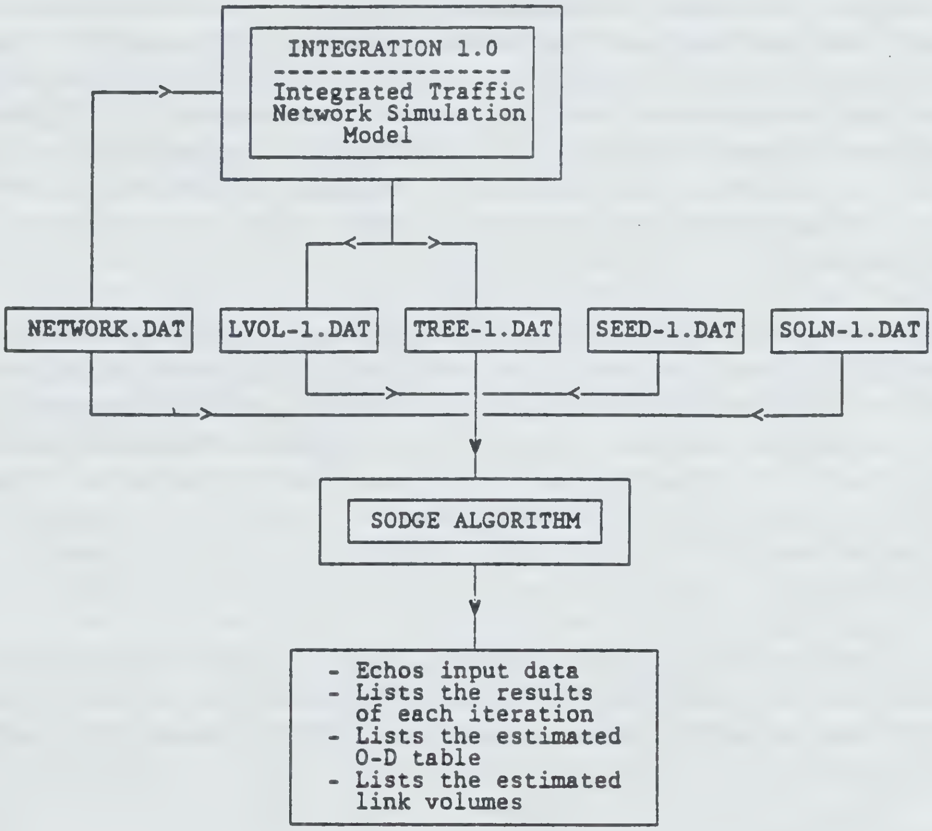
c. Computer Implementation of the Selected Algorithm

The revised information-minimization algorithm (Van Zuylen, 1981) was implemented as a new computer program by Noxon (1988) to allow model inputs which are compatible with the INTEGRATION simulation model. The resulting program, called SODGE (Synthetic Origin-Destination GEnerator), requires 3 essential input files. The first is a network description file, which lists the network links. The second file contains the link traffic flows, while the third contains a minimum path tree matrix for the given network conditions. Two other input files are optional, namely a seed O-D matrix and the actual O-D matrix, if available. The former assists in initiating the search amongst the range of feasible solutions, while the latter, if known, allows the user to check the accuracy with which a true matrix can be recreated.

As SODGE was developed to provide O-D counts to the INTEGRATION simulation model, the network description file for both models was formulated for dual compatibility. In addition, the SODGE link volume and minimum path tree input files were configured such that they could automatically be generated using INTEGRATION. Consequently, a given

network could be analyzed using INTEGRATION to determine minimum path trees and link flows, and with these SODGE could be run to retroactively determine the most likely O-D matrix governing the network's operation. This procedure is illustrated in Figure 2, and was first utilized to determine the reliability and accuracy with which SODGE could reproduce a known matrix, supplied only with link flows and minimum path trees. However, in practice

Figure 2: Synthetic O-D Generation Procedure Utilized by SODGE



LVOL-1.DAT:	Contains the link volumes generated by INTEGRATION 1.0 for the time interval being analyzed.
TREE-1.DAT:	Contains the minimum path trees generated by INTEGRATION 1.0 for the time interval being analyzed.
NETWORK.DAT:	Describes the network used both by SODGE and INTEGRATION 1.0.
SEED-1.DAT:	Contains the seed matrix (real or default) for the time interval being analyzed.
SOLN-1.DAT:	Contains the actual solution matrix (if known) for the time interval being analyzed.

SODGE would be used to generate an estimate of the unknown O-D matrix for use within the INTEGRATION model, which in turn would evaluate different network control strategies.

d. SODGE Measures of Convergence

In order to monitor and evaluate the convergence of the SODGE algorithm, the program calculates three statistical indicators at the conclusion of each iteration.

The first measure is the root mean squared difference (RMSD) between the cell values of successive iterated solution tables. This value decreases as successive iterations produce more similar solution tables and the deviations between cell values for successive iterations are minimized. The second measure is the root mean squared error (RMSE) between the input set of observed link flows and the estimated link flows that are produced by feeding the iterated trip table back into the network. These two statistical measures are produced for each iteration in all cases. The third statistical quality indicator is the RMSE (in percentage form) between the cell values of the current trip table estimate and those of the actual trip table, if the latter is provided by the user.

If no solution matrix is available, convergence to a solution may be indicated by a stabilization of the trip cell RMSD figure between consecutive iterations. However, the algorithm tends to give a series of RMSD stabilizations at different levels of actual convergence. It is thus better to judge convergence using the link flow RMSE, which will consistently stabilize at the optimal convergence. Convergence of link flows indicates that the matrix, while perhaps not the exact one, can reproduce the observed link flows at a desired level of accuracy. If this is the case, the approximate O-D solution matrix is likely to be acceptable in practical terms for the purposes of the study.

In practice, the actual matrix is of course always unknown, as it is the object of the search. However, during the testing of SODGE, the search for a known O-D matrix was performed to determine the likely range of errors and problems associated with searches in practice where the true matrix is unknown.

e. SODGE Output Listing

The output for SODGE is structured in four parts. The first part echoes the input data and the seed matrix. The next section lists the results of each iteration in terms of its convergence measures. The third part contains the final O-D table estimate, while the last section lists the estimated link volumes next to the observed link volumes so that both relative and absolute comparisons can be made. The above version of SODGE has been modified so that it can be used for iterative on-line calculations of a series of O-D matrices for consecutive time slices during a peak period. This approach and the details of its implementation are described next.

3. APPROACH FOR SEQUENTIAL GENERATION OF ON-LINE O-D COUNTS

The previous section indicated how the SODGE implementation of Van Zuylen's (1981) synthetic O-D generation technique could be used to automatically interact with INTEGRATION to derive one O-D matrix at a time. This section illustrates how the same procedure can be utilized to derive a series of consecutive O-D matrices for an entire peak period.

a. Methodology

As the traffic demands within a peak period are not necessarily uniform, clearly no single O-D table can accurately represent the demand pattern over the whole period. Therefore, the entire peak period to be analyzed is broken down into a series of consecutive time slices, each time slice having its own separate O-D table. As a first step, one could generate the O-D matrices for an entire peak period by simply running SODGE for each time slice by itself, without accounting for any interactions.

However, as the generation of an O-D matrix from scratch involves a large number of iterations, and as the quality of an O-D matrix generated without some reliable a priori knowledge is usually not very high, further significant performance enhancements are possible. These involve the use of the previous time slice's O-D matrix as the seed for the derivation of the next time slice's matrix. This approach is illustrated in Figure 3 for a sample sequence of two consecutive time slices.

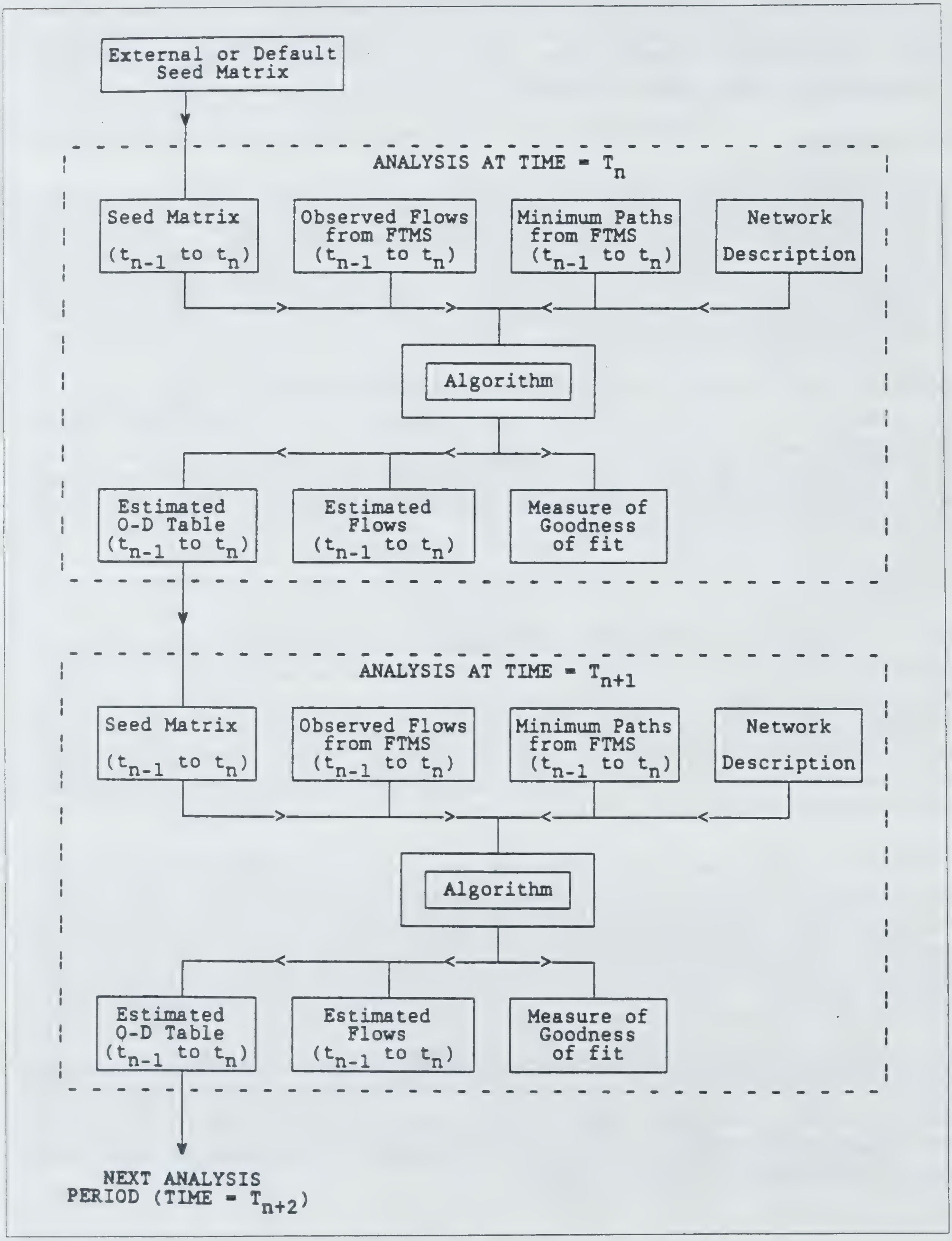
b. Consequences

If there is any relationship between the true O-D matrices of consecutive time-slices, the O-D estimate of the first period will make a much better seed for the second stage than would a random or uniform seed. The first consequence of this is that fewer iterations would be required to estimate the next matrix. This is an important efficiency if these O-D estimates are to be made based on on-line traffic counts in real-time. More importantly, if the O-D matrix estimated for the previous time slice was a good fit, its use as a seed should also considerably improve the accuracy of the O-D prediction for the next time slice.

If there is a consistent non-trivial relationship among a time-series of O-D matrices, this technique would efficiently retain the general structure of the O-D pattern over the entire period. However, it would also selectively scale the entire matrix and/or selective entries in the matrix, in view of any changes in observed link flow counts. The result would be more accurate on-line O-D estimates which are responsive to real-time traffic flow counts provided by FTMS detectors.

In an off-line situation, the above features permit an efficient and economical estimation of a sequence of O-D matrices which reproduce the link flows which are observed during the peak period. In addition, when the technique is applied using on-line data, it will estimate in real-time the unique O-D matrices for a particular day's peak period in view of the unique traffic flows that are observed on that particular day.

Figure 3: Proposed On-Line Synthetic O-D Generation Procedure



c. Description of the Test Network and its FTMS

To illustrate the potential of the above on-line O-D generation technique, some sample test runs were performed using data for the Burlington Skyway FTMS on the Queen Elizabeth Way (QEW) between Toronto and Niagara Falls, Ontario. The general location of the Burlington FTMS system is illustrated in Figure 4a, while a detail of the actual network is provided in Figure 4b.

As shown in Figures 4a and 4b, the QEW is a major provincial highway between Toronto and Niagara Falls and cuts across the Hamilton Harbor at the west end of Lake Ontario. As the freeway crosses the Burlington Canal via the Burlington Skyway Bridge, its final configuration will provide three fully detectorized lanes in each direction. In addition, a four lane arterial parallel to the QEW provides a second route which acts as a diversion alternative in case of an incident on the bridge (Delsey and Stewart, 1985). This diversion route is signalized and fully detectorized.

At the time of this study, only the detectors for the southbound portion of the system were fully operational, as the northbound portion of the system was still under construction. Consequently, the test runs on the Burlington Skyway only considered the southbound traffic network and traffic demands. The southbound Burlington Skyway network was coded and digitized in March, 1988 using 100 links and 73 nodes, of which 10 were also zone centroids. The coded network is illustrated in Figure 5.

Figure 4a: General Location of the QEW and the Burlington Skyway FTMS

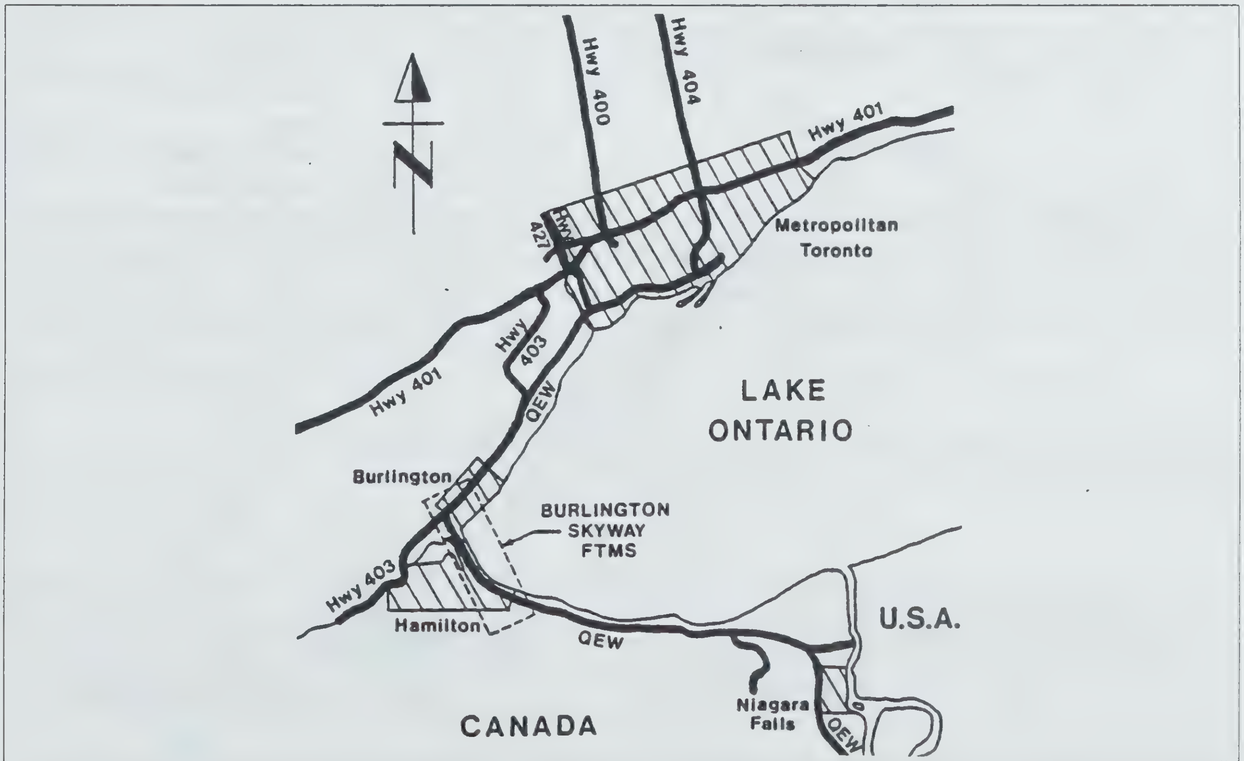


Figure 4b: Detail of Area Controlled by Burlington Skyway FTMS

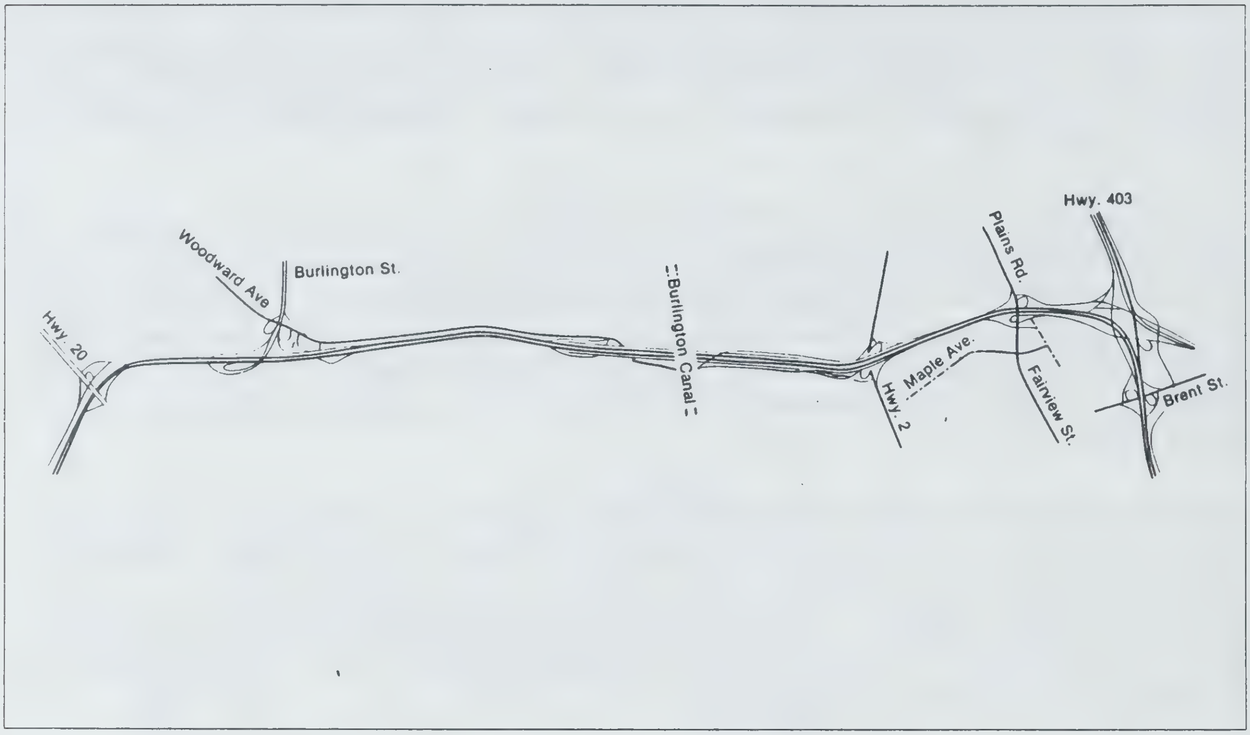
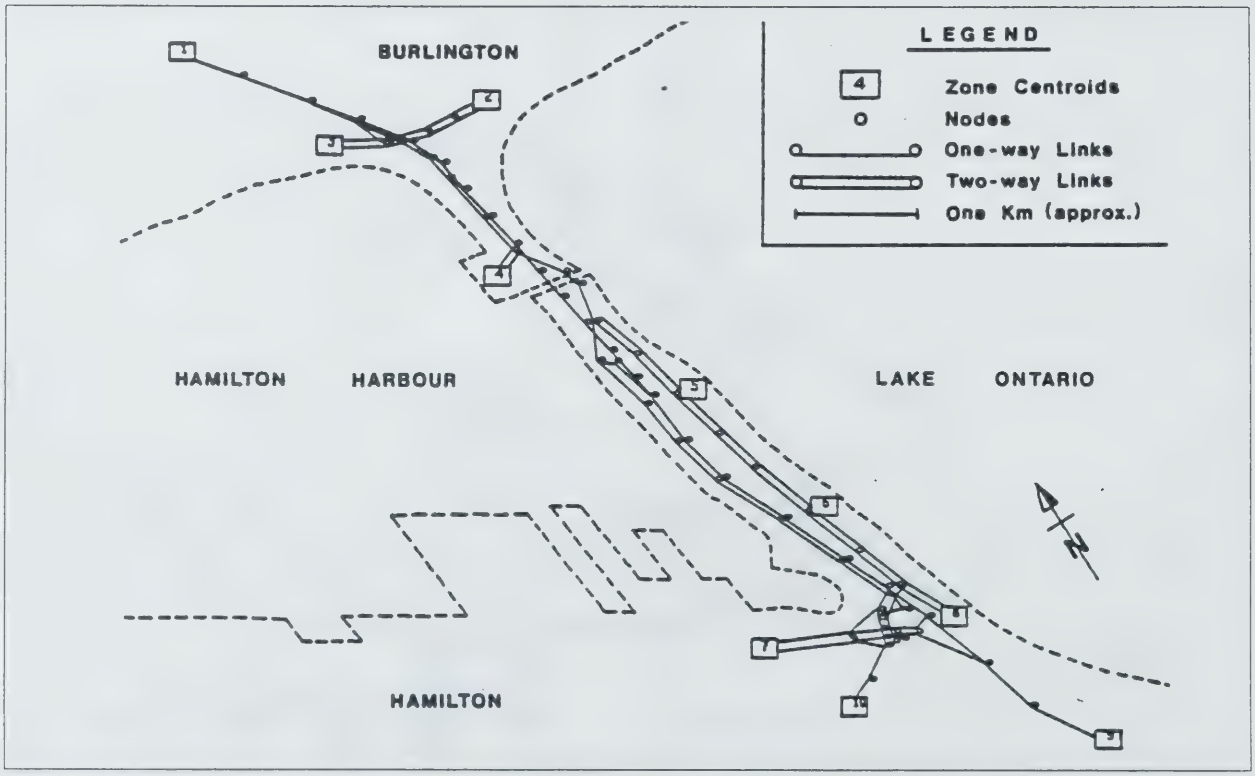


Figure 5: Network Representation of Southbound Burlington Skyway FTMS



d. Details

During the trial evaluation of the above procedure, a number of details had to be resolved, such as the duration of the time-slices and the updating rate of the minimum path trees, as discussed below.

A time-slice duration of 15 minutes was considered to be short enough to allow the capturing of dynamic changes in the O-D pattern, while also providing sufficiently stable link flow counts to SODGE. The whole two-hour peak period analysis was thus based on an eight-slice simulation of a typical peak period. The objective was to determine if the sequential estimation procedure could successfully back-calculate prevailing O-D patterns and their changes.

Since the current version of SODGE is set to evaluate flows for all-or- nothing route assignments, INTEGRATION was used to assign traffic flows to all-or-nothing assignments for 15 minutes at a time. In addition, since INTEGRATION starts its evaluations with networks which are initially empty, a state of equilibrium was allowed to develop during the first 15 minutes before any link summaries were computed. This time allowed all O-D patterns to fully propagate through the network, since the maximum trip length in the network was about 8 minutes. Finally, to provide an analysis of equilibrium conditions, all signal timings were held constant during the entire two-hour peak period.

4. RESULTS OF ON-LINE O-D GENERATION TESTS

The potential of the proposed approach was assessed using a systematic evaluation of four sets of related experiments. The variations within and between each set of tests was utilized to quantify the main factors which contribute to the prediction error under different operating conditions. A description of these experiments is provided below, while the results are summarized in Tables 1a, 1b and 1c.

a. Experimental Trial I

The first experiment consisted of runs A and B, where the INTEGRATION simulation model was utilized to simulate traffic conditions on the Burlington Skyway for a constant demand O-D matrix for 2 hours. Link flow and minimum path tree estimates were generated by the simulation model for each time slice, after the initial 15 minute start-up, and these files were analyzed using SODGE.

Run A used a uniform seed O-D matrix for the first time-slice, while Run B used the actual O-D matrix as the seed. The results, which are shown in Table 1a, indicate three important facts.

First, the analysis of the first time-slice with a uniform seed matrix requires many more iterations (10) than any of the subsequent time-slice analyses (2-4). This indicates the efficiencies that are achieved if the solution matrix for a previous time slice is utilized as a seed matrix for a subsequent time slice.

Table 1a: Constant O-D Demand Patterns for the Entire Hour Period

	RUN A O-D Demand constant Initial seed = 100 Epsilon = 0.1			RUN B O-D Demand constant Init. seed = Act. soln. Epsilon = 0.1		
TIME PERIOD	# OF ITER	FLOW RMSE	OD TABLE RMSE %	# OF ITER	FLOW RMSE	OD TABLE RMSE %
1						
2	10	5.65	46.73	2	5.74	2.95
3	2	9.73	47.41	2	10.26	4.82
4	3	8.81	43.59	3	8.80	4.97
5	4	10.19	47.26	4	10.54	6.53
6	4	10.33	45.19	4	10.66	7.02
7	4	8.73	46.17	4	8.39	4.82
8	4	8.53	46.00	4	8.43	5.62

Table 1b: Increased O-D Demand Pattern from Time 1.0 hrs to 1.5 hrs

	RUN G O-D Demand varies Constant seed = 100 Epsilon = 0.1			RUN D O-D Demand varies Initial seed = 100 Epsilon = 0.1			RUN F O-D Demand varies Init. seed = Act. soln. Epsilon = 0.1			RUN H O-D Demand varies Each seed = Act. soln. Epsilon = 0.1		
TIME PERIOD	# OF ITER	FLOW RMSE	OD TABLE RMSE %	# OF ITER	FLOW RMSE	OD TABLE RMSE %	# OF ITER	FLOW RMSE	OD TABLE RMSE %	# OF ITER	FLOW RMSE	OD TABLE RMSE %
1												
2	10	5.65	46.73	10	5.65	46.73	2	5.74	2.95	2	5.74	2.95
3	10	8.35	47.22	2	9.73	47.41	2	10.26	4.82	2	9.11	4.57
4	12	10.96	43.83	3	8.81	43.59	3	8.80	4.97	2	10.37	5.02
5	9	115.03	66.48	8	121.37	67.57	8	121.97	47.85	10	109.86	43.77
6	13	15.07	48.28	8	21.40	48.35	8	21.27	22.34	4	11.62	6.21
7	9	110.32	65.54	10	115.76	65.68	10	116.86	64.60	10	108.70	61.95
8	10	11.78	45.61	8	17.03	44.53	10	12.82	5.54	2	10.24	5.33

Table 1c: Increased O-D Demand Pattern with Epsilon = 0.01 Rather than 0.1

	RUN E O-D Demand varies Initial seed = 100 Epsilon = 0.01			RUN I O-D Demand varies Each seed = Act. soln. Epsilon = 0.01		
TIME PERIOD	# OF ITER	FLOW RMSE	OD TABLE RMSE %	# OF ITER	FLOW RMSE	OD TABLE RMSE %
1						
2	18	6.70	46.93	9	7.05	3.54
3	9	7.94	47.54	10	8.06	4.16
4	9	9.62	43.92	9	9.50	4.60
5	16	113.15	66.26	17	113.27	44.60
6	16	13.92	48.31	12	13.21	5.73
7	17	111.71	65.17	16	112.25	63.11
8	16	10.45	45.76	10	9.64	4.90

Second, even though run B was provided with the actual solution matrix, the O-D table it estimated was not exactly the same as the one that was used in the simulation model. The main reason for this difference is the presence of traffic signals in the network, which cause link arrival and departure rates to be non-uniform. This discrepancy is also illustrated by the lack of a perfect convergence of the link flows.

Finally, even though the link flows in Run A and Run B converged to roughly the same link flow error level, the deviation from the actual true matrix was much larger for the analysis seeded with a uniform matrix (43-47%) than for the analysis which was seeded with the true matrix (2-7%). This indicates that two solutions can have comparable link flow convergences but still differ substantially in their agreement with the actual matrix.

b. Experimental Trial II

While Runs A and B were based on the simulation model outputs for a constant traffic demand pattern, Runs G, D, F and H considered a traffic demand pattern which was constant for 1 hour, increased for certain O-D pairs for 30 minutes, and then returned to its original state for the final 30 minutes. The original and the changed O-D matrix are illustrated in Tables 2a and 2b, while the consequent statistics for each of these runs are illustrated in Table 1b.

Table 2b: Modified O-D Matrix for Time 1.0-1.5 hrs.

It is important to note that after 1 hour, the INTEGRATION simulation model increased the vehicle departure rates at the respective origins immediately, but that all relevant link flows did not increase until these vehicles reached those links downstream. Consequently, there is a lag in the response of the link flow rates, which at worst is equal to the travel time between the two most separated O-D pairs, or approximately 8 minutes. This lag implies that the link flows for these time-slices would be a weighted average of the previous time- slice's O-D rate

Table 2a: Original O-D Matrix for Time 0-1.0 hrs and 1.5-2.0 hrs

Destinations across

Orig down	1	2	3	4	5	6	7	8	9	10	SUMS
1	0	180	180	60	60	60	180	60	900	180	1860
2	0	0	180	30	30	30	90	30	90	90	570
3	0	180	0	30	30	30	30	30	90	30	450
4	0	0	0	0	60	30	30	30	30	30	210
5	0	0	0	0	0	0	60	0	60	60	180
6	0	0	0	0	0	0	60	60	60	60	240
7	0	0	0	0	0	60	0	60	180	120	420
8	0	0	0	0	0	60	60	0	0	60	180
9	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0
SUMS	0	360	360	120	180	270	510	270	1410	630	

Table 2b: Modified O-D Matrix for Time 1.0-1.5 hrs

Orig down \ Destinations across	1	2	3	4	5	6	7	8	9	10	SUMS
1	0	240	240	60	60	60	360	180	1200	300	2700
2	0	0	240	30	30	30	90	30	90	180	720
3	0	240	0	30	30	30	30	30	90	60	540
4	0	0	0	0	60	60	30	30	60	60	300
5	0	0	0	0	0	0	60	0	60	60	180
6	0	0	0	0	0	0	60	60	60	60	240
7	0	0	0	0	0	60	0	120	240	240	660
8	0	0	0	0	0	60	90	0	0	120	270
9	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0
SUMS	0	480	480	120	180	300	720	450	1800	1080	

and the new O-D flow rate. This so called "transient" effect should disappear in the second time slice following the change, when the transition will be complete.

Run G (see Table 1b) provides the results for an analysis where the SODGE routine was seeded with a matrix of uniform cell values (equal to 100) for each time slice. As the analysis starts from scratch at the start of each time slice, the number of iterations stays relatively high (9-13). Also, due to the presence of transients, the link flows of time-slices 5 and 7 are shown to converge very poorly, and the estimates of the O-D matrix in each case are also less accurate. These results should be compared to Run D, where SODGE was seeded with a uniform matrix, but was allowed to use its predicted O-D matrix from each time-slice as a seed for the next time-slice. Both the flow and the O-D cell errors are shown to be the same as for run G, but the number of iterations required to find this comparable solution is shown to be reduced in most cases.

Run F indicates the results for a situation where the seed provided to the first time slice is the actual solution matrix; the O-D of each subsequent time slice is then calculated using the previous slice's solution as its seed. As shown, this results in both a significantly reduced number of iterations for the first time-slice analysis, and a consistent number of iterations for all the subsequent time-slices. Similarly, the degree of convergence of link flows is roughly the same, as is the increase in the link flow error during the transition periods. However, the agreement with the actual O-D table is much better for Run F, even after the two major changes in the traffic pattern. The findings for Run F emphasize the importance of having a good seed matrix for the first time-slice of the analysis. Even when the actual O-D cell values change, having some knowledge of the underlying pattern appears to be of considerable

assistance. Furthermore, it is interesting to note that even after the matrix has undergone a change, the predicted matrix for the final time slice is still very close to the actual matrix.

Finally, in Run H SODGE was provided with the correct seed matrix for each time slice. The results are obviously the best of any of the runs, but some error still remains, especially during the transient periods. It is important to compare the SODGE performance in Run F against that in Run H, and to note that relatively good results can be achieved by seeding only the first time slice with the actual matrix. An overview of the relationships among the results for Runs G, D, F and H (all in Table 1b), is provided in Figure 6. The results for Runs A and B (Table 1a) are compared to the results for Runs D and F (Table 1b) in Figure 7.

Figure 6: Comparison of Fit for Different Seed Matrices

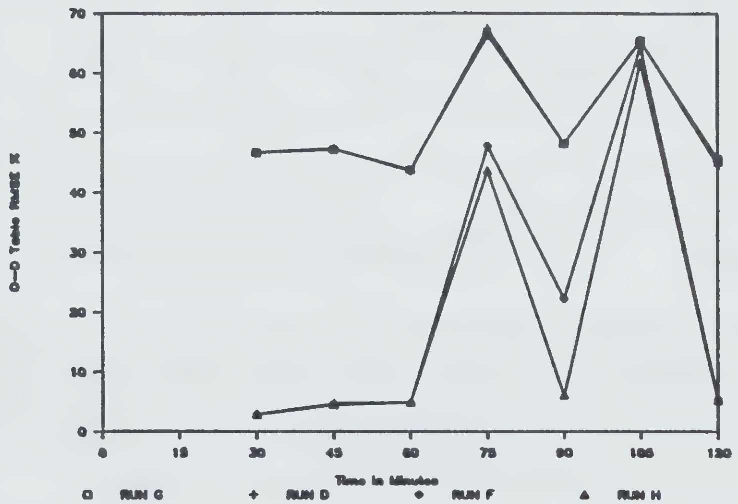


Figure 7: Comparison of Fit for Constant vs. Changing Demands

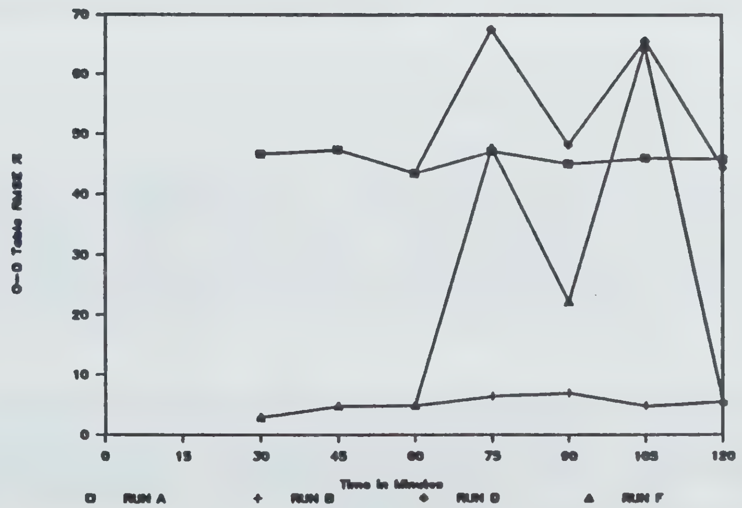
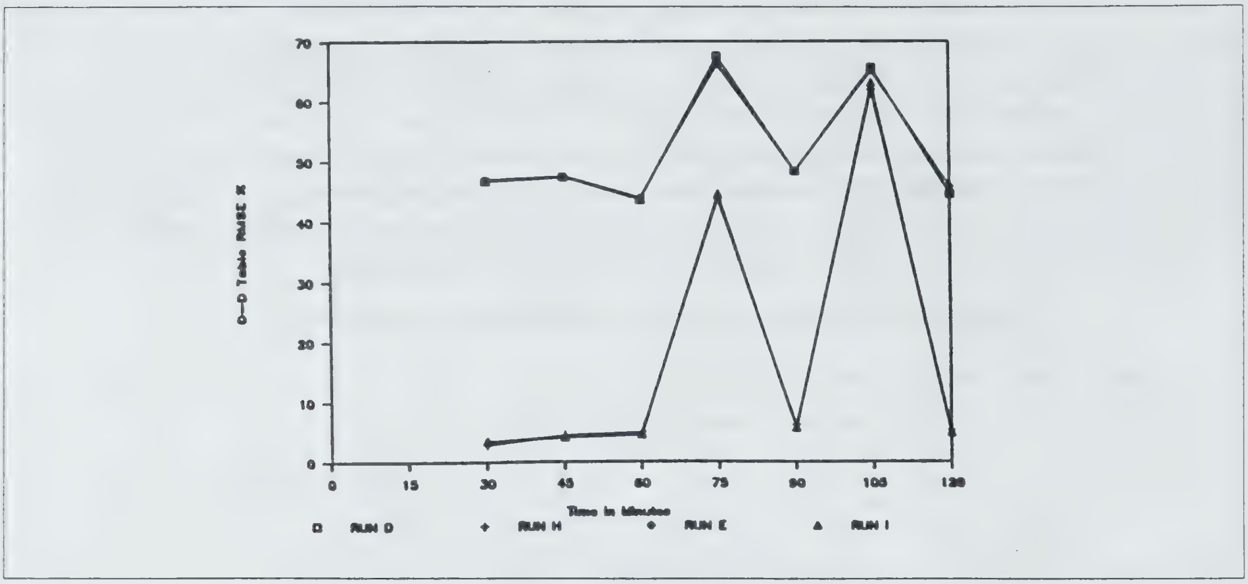


Figure 8: Comparison of Fit for 2 Different Stopping Criteria



c. Experimental Trial III

The third experiment involved an analysis of the implications of utilizing a different epsilon value for identifying the onset of convergence. Runs E and I have results very similar to Runs D and H, respectively, as shown in Figure 8. Dropping the epsilon from 0.1 to 0.01 significantly increased the number of iterations, marginally increased the degree of flow convergence, and has only a negligible effect on the accuracy of the estimated O-D table.

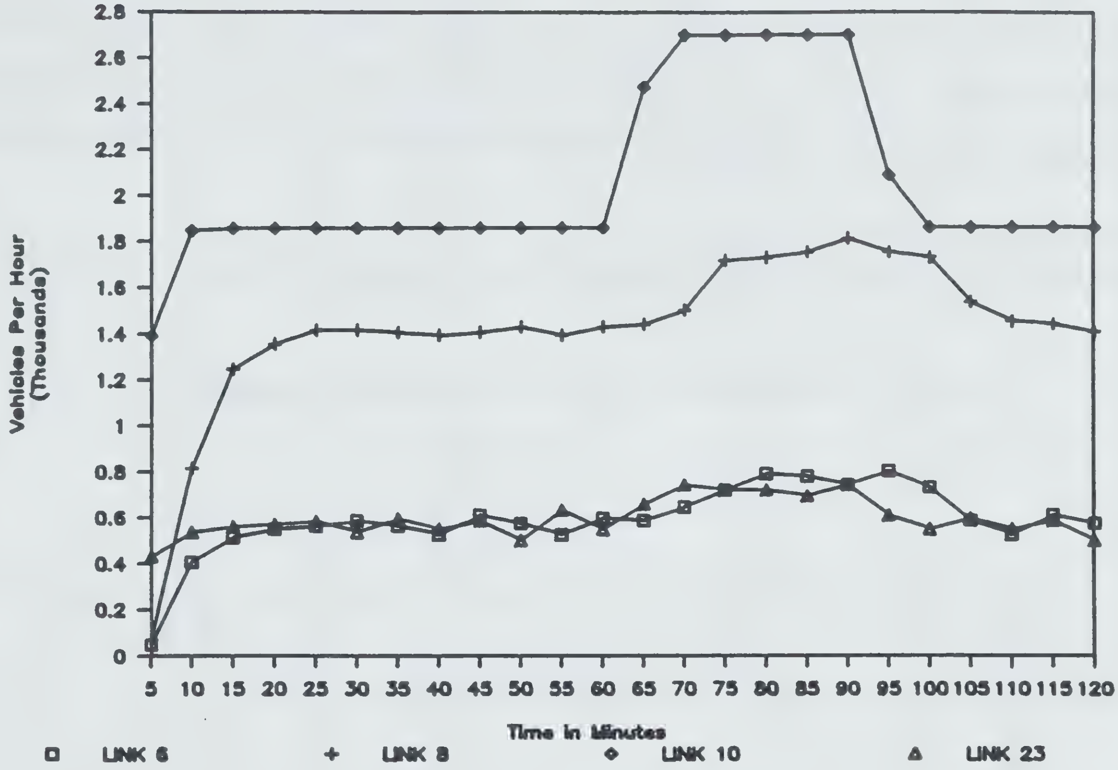
Consequently, the use of an epsilon value of no smaller than 0.1 seemed appropriate for the tests carried out using this network. However, this value is likely to be different for different networks and perhaps even for different traffic conditions. It should therefore be non-dimensionalized and expressed in a format which is unbiased by the scale of the network and/or its traffic pattern.

d. Experimental Trial IV

The fourth and final experiment involved an analysis of the implications of using a 5-minute versus a 15-minute analysis interval. This analysis allowed for a more microscopic look at the dynamic behavior of the traffic within the network, and the consequent implications for the on- line generation of O-D's. Figure 9a illustrates the traffic flow rates on 4 different links in the network, namely:

When one compares the increase in traffic volume on the freeway links (L8 and L10), to the increases on the surface streets (L6 and L23), it is clear that the traffic increase on the freeway is much more pronounced than on the surface streets. This is to be expected, as the change in the O-D pattern affects primarily the freeway trips.

Figure 9a: Change in 5-Minute FLow Rates on Links 6,8,10,23



When one compares the first freeway link (L8) to the last freeway link (L10), one can also detect the lag in the transient effect for the downstream link (L10). This lag is approximately equal to the travel time from Zone 1 to Zone 9. It significantly complicates the synthetic O-D analysis, as the effect of a change in O-D pattern cannot be detected on the final downstream link until about 10 minutes after the O-D pattern has changed. Synthetic O-D solutions based on traffic flows during this initial 10 minute transient would therefore incorrectly allocate the increased flows, on the first few links, to the same origin but a nearer destination. Of course, following a decrease in traffic flow for an O-D pair, the reverse effect would take place.

The above problem indicates that it is difficult to define what an O-D matrix for a certain time period really implies, as vehicles starting their trips in one time period are likely to finish their trip in a subsequent time period. Consequently, it is difficult to determine if such trips belong to the O-D matrix of the first or the second time slice.

The results for the iterative SODGE application every 5 minutes are illustrated in Figure 9b and Table 3. This analysis was initiated with the correct seed matrix after 20 minutes, and all subsequent applications of SODGE were then seeded with the O-D solution matrix from the previous 5 minute period.

As shown, during the first 60 minutes, the number of iterations, the link flow error and the O-D matrix error vary somewhat about a relatively stable average value. Then, after the increase in the O-D matrix at time 60 minutes, the dramatic transient results in a considerable error in the link flow convergence and the O-D matrix estimation during the next two 5-minute time periods. Subsequently, the solutions generated by the algorithm again stabilize, until the O-D demand is dropped after 90 minutes.

It is interesting to note that while the link flow error peaks for the time slice which is 5 to 10 minutes after the change in O-D flows occurs, the O-D matrix error has already begun to

Figure 9b: Results for 5-Minute Intervals and Correct Initial Seed

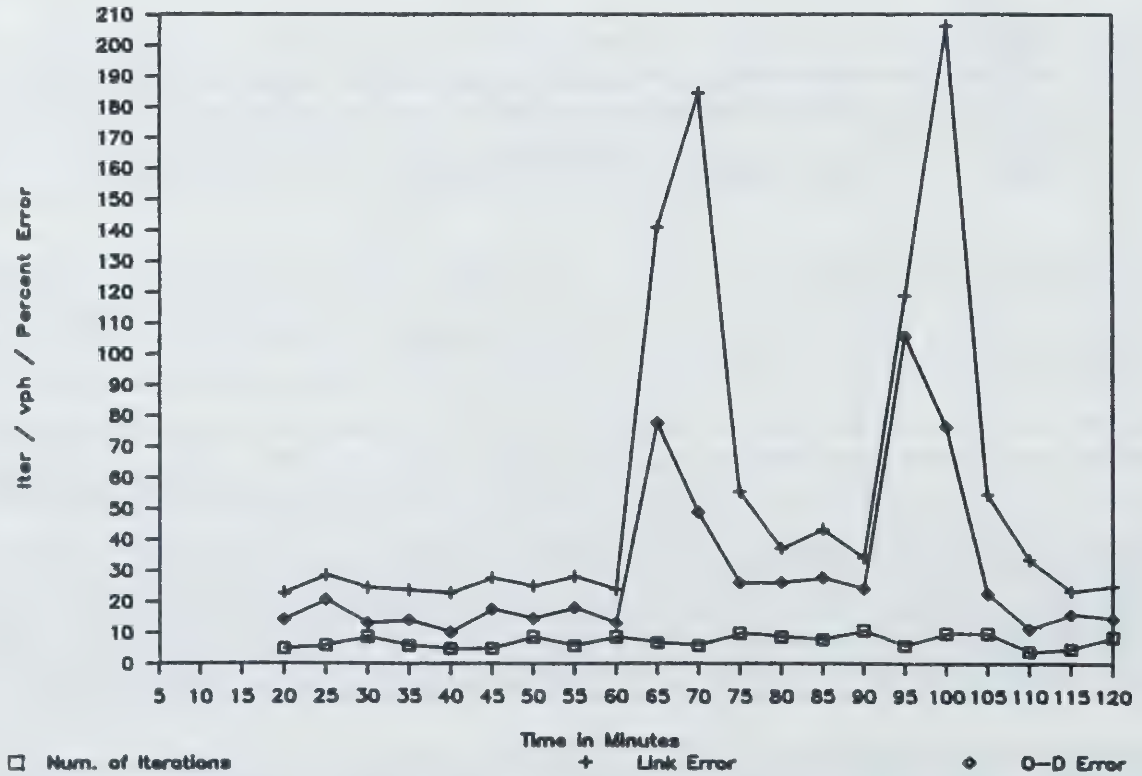


Table 3: Results for 5-Minute Intervals and Correct Initial Seed

TIME SLICE	TIME (Min) FROM	TO	NUMBER OF ITERATIONS	LINK FLOW ERRORS	O-D TABLE ERROR(%)
1	0	5			
2	5	10			
3	10	15			
4	15	20	5	23.0	14.3
5	20	25	6	28.8	20.9
6	25	30	9	24.7	13.3
7	30	35	6	24.0	14.3
8	35	40	5	23.0	10.3
9	40	45	5	28.0	17.8
10	45	50	9	25.2	14.7
11	50	55	6	28.6	18.4
12	55	60	9	24.2	13.4
13	60	65	7	141.3	78.1
14	65	70	6	184.8	49.2
15	70	75	10	55.8	26.3
16	75	80	9	37.4	26.4
17	80	85	8	43.7	28.0
18	85	90	11	34.4	24.4
19	90	95	6	119.0	105.9
20	95	100	10	206.4	76.9
21	100	105	10	54.9	22.8
22	105	110	4	33.8	11.5
23	110	115	5	23.6	16.8
24	115	120	9	25.5	14.9

decrease significantly. Consequently, during the time slice which lasts from 10 to 15 minutes after the O-D flow increase/decrease, the O-D matrix provides a good fit once again.

5. DISCUSSION OF THE RESULTS AND THEIR SIGNIFICANCE

In most network-oriented traffic management studies it is important to determine the prevailing Origin-Destination traffic demands during a peak period in order to estimate the indirect diversion impact of any proposed control strategies, or to determine the direct diversion impacts of control strategies which are deliberately intended to result in a re-routing of traffic. The need to evaluate the growth and decay of traffic patterns during a peak period requires the analyst to consider the time varying O-D demands of the network explicitly. As it is either impractical or uneconomical to obtain time-varying O-D's by direct survey methods, it becomes necessary to utilize indirect methods. These synthetic O-D methods, while subject to some error and various other technical problems, provide the next best solution, as often no alternative approach to obtaining these data is available.

a. Summary of Initial Findings

The results presented in this paper have indicated that it is feasible to automatically generate a sequence of O-D matrices for a series of time-slices during a peak period. Such matrices can be used in conjunction with freeway control or diversion models for off-line pre- evaluation of different strategies using historical traffic counts, or for on-line generation of diversion strategies using real-time traffic flow measurements.

The use of a time-slice's solution O-D matrix as the seed for the subsequent slice appears to reduce the number of iterations required to achieve a certain level of accuracy, as compared to using a blank or uniform seed matrix for each new time-slice. This efficiency in computation time is especially useful in real-time control applications.

The use of a sound initial seed matrix at the start of a control period has benefits throughout the entire control period, even if the flow rates for a number of O-D pairs may change significantly. The structure of the initial seed is usually retained throughout the analysis period and assists considerably in selecting the most appropriate O-D matrix from amongst the often numerous possibilities.

b. Problems Unique to Synthetic O-D's for Freeway Control

Traffic demands within congested freeway networks are never in full equilibrium. Instead, they appear to be always in some state of dynamic flux or transition. Consequently, problems arise due to the transients which occur when traffic patterns change, as these changes require a finite period of time to manifest themselves on all the downstream links that will be utilized by the given O-D.

Similar problems may also arise when queues cause two different link flow rates along a given path, one on the upstream end of the bottleneck, and one on the downstream end. In this situation, the synthetic O-D program may mistake the resulting traffic flow observations as being indicative of two shorter trips, rather than one longer one.

It is expected that in practice the above transient effects may not be as drastic or dramatic as the nearly instantaneous 50% increase in traffic flows which was utilized in this paper's work. In actual networks it is more likely that traffic demands will change gradually during a 15 to 30 minute period, in which case the problems generated due to transients will be lessened, and perhaps become insignificant.

c. Recommended Further Work

Clearly, the proposed procedure should be implemented using real data from an FTMS and UTCS system and compared to the O-D's as estimated from a detailed driver survey. However, it is likely that in practice the true O-D matrices will never be be available to assess the quality of the solutions obtained. In this case, the relative magnitudes of the errors, as estimated in the sample runs of this paper, could be a guide as to the likely margin of error that would be present in situations where the true matrix is unknown.

To address some of the above transient problems, it may be helpful to utilize the algorithm with fractional "link use" probabilities. In this case, the path that is taken by vehicles between a given O-D pair may be assigned decreasing use probabilities along its length to reflect the decreased likelihood that the effects of the shift in that O-D demand have propagated a certain distance away from its origin. Similarly, different probabilities may be assigned to links before and after a bottleneck location to indicate the fraction of drivers from a particular O-D pair that are likely to be stuck in the queue.

Finally, it is proposed that the above analysis be repeated for a wider corridor in which more alternate routes are available. While it would be much more difficult to trace the causes and effects of any transients, this type of network application would be more representative of corridors in which one freeway can be avoided by traveling on any one of up to 3 or 4 alternate routes.

REFERENCES

Cascetta, E. (1984), "Estimation of Trip Matrices from Traffic Counts and Survey Data: A Generalized Least Squares Estimator", Transportation Research Record 18B, pp. 289-299.

Delsey, M.J. and S.E. Stewart (1985), Queen Elizabeth Way - Burlington Skyway Traffic Management System, Transportation Forum Volume 2 - 2. pp. 68-72.

Hendrickson, C. and McNeil, S. (1984), "Estimation of Origin-Destination Matrices with Constrained Regression", Transportation Research Record 976, TRB, pp. 25-32.

Maher, M.J. (1983), "Inferences on Trip Matrices from Observations on Link Volumes: A Bayesian Statistical Approach", Transportation Research, Volume 17B, pp. 435-447.

Noxon, G. (1988), "Development and Testing of a Model to Estimate Origin-Destination Matrices from Link Counts", Undergraduate Technical Report (unpublished), Department of Civil Engineering, Queen's University, Kingston, Canada.

Van Aerde,M., S.Yagar, A. Ugge and E.R. Case(1987), A Review of Candidate Freeway/Arterial Corridor Traffic Models, Annual Transportation Research Board Meeting, Washington D.C.

Van Aerde,M., J. Voss, A. Ugge and E.R. Case(1988), An Integrated Approach to Managing Traffic Congestion in Combined Freeway and Traffic Signal Networks, Proceedings, ITE Conference on Traffic Congestion 88, Tampa, Florida.

Van Aerde,M., J. Voss, A. Ugge and E.R. Case(1989), An Integrated Approach to Managing Traffic Congestion in Combined Freeway and Traffic Signal Networks, ITE Journal - Volume 59, Number 2.

Van Vliet, D. and Willumsen, L.G. (1981), "Validation of the ME2 Model for Estimating Trip Matrices from Traffic Counts", Eighth International Symposium on Transportation and Traffic Theory, University of Toronto, Canada, pp. 191-198.

Van Zuylen, H.J. (1981), "Some Improvements in the Estimation of an O-D Matrix from Traffic Counts, Eighth International Symposium on Transportation and Traffic Theory, University of Toronto, Canada, pp. 183-190.

Van Zuylen, H.J. and Willumsen, L.G. (1980), "The Most Likely Trip Matrix Estimated from Traffic Counts", Transportation Research, Volume 14B, pp. 281-293.

APPENDIX D:

MODELING THE POTENTIAL EFFECTIVENESS OF THE BURLINGTON SKYWAY FREEWAY TRAFFIC MANAGEMENT SYSTEM DURING PERIODS OF RECURRING AND NON-RECURRING TRAFFIC CONGESTION

M. Van Aerde, J. Voss and Y. Blum

ABSTRACT

A model, called INTEGRATION, was developed to evaluate and optimize the traffic controls in an integrated freeway/traffic signal corridor. The model is especially suited to model the interaction of different control strategies, such as traffic diversion, improved incident response and/or real-time traffic signal timings, during periods of recurring or non-recurring congestion. This paper demonstrates the availability of the required demand and supply input data for the model, indicates how the model can then be utilized to evaluate different control strategies, and illustrates the types of results that can be obtained. This demonstration analysis was carried out for the Burlington Skyway Freeway Traffic Management System near Hamilton, Ontario, which monitors and controls an elevated skyway across a canal and a parallel signalized surface route across a lift bridge. The skyway has accident and incident rates which are much higher than the average rate for similar facilities. Consequently, the model is utilized to examine how improved traffic controls can minimize the impact of these incidents/accidents.

The results of this preliminary analysis indicate that, for the specific incident type that was analyzed, real-time optimization of traffic signals along the parallel arterial provides an approximately constant reduction in delay for all durations of incidents. In contrast, real- time rerouting or diversion of traffic is of little benefit prior to an incident, but becomes increasingly more beneficial for longer incident durations. The joint real-time optimization of signal timings and re-routing of traffic reduces the delays associated with a 30-minute incident to a value which is below the original delays for a non-optimized "no incident" scenario.

1. INTRODUCTION

The Burlington Skyway is located at the most western end of Lake Ontario, and crosses the canal which connects Hamilton Harbor from the main body of Lake Ontario. There is considerable commercial marine traffic in and out of the harbor, and consequently, an elevated Skyway was constructed across the harbor entrance canal to supplement the arterial route which includes a lift bridge, as shown in Figure 1a. At the time of this analysis, both the Burlington Skyway and the parallel arterial route provided 2 lanes in each direction.

The Burlington Skyway Corridor is a major bypass around the City of Hamilton and the composition of the traffic within it is a mixture of commuter traffic between the Niagara Peninsula and Metro Toronto, commuter traffic between Hamilton/Stoney Creek and Burlington, and local traffic destined for locations near the Skyway, such as the Canadian Center for Inland Water Studies. The corridor has experienced a considerable growth in traffic, and during the peak summer months of 1988, the peak ADT was observed to occasionally exceed 100,000 veh/day. Consequently, large queues develop on the Skyway when an incident or weather conditions reduce its capacity, or in front of the lift bridge when pleasure craft enter/exit the harbor. The peaking characteristics of traffic volumes throughout the day (as of 1981) in Figure 1b, while the frequency of accidents is illustrated in Figure 2. As illustrated in Table 1, the rate of such accidents exceeds the provincial average by almost a factor of 3.

The presence of two distinct routes between the north and south end of the corridor provides for considerable diversion opportunities, when required. Under normal conditions, the freeway route is clearly the preferred choice for thru traffic in view of its shorter distance, higher speed and capacity, and the arterial is utilized only by local traffic. However, when incidents or weather conditions cause a partial or complete closure of the elevated Skyway, the arterial route becomes a credible diversion route. The response plan associated with the use of this diversion route requires the use of CMS messages to notify the drivers of the recommended diversion, and a retiming of the traffic signal splits and cycle times to provide additional capacity for the increased traffic flows on the arterial. Alternatively, when the lift

Figure 1a: Detailed Layout of the Burlington Skyway and Parallel Arterial

(Delsey and Stewart, 1985)

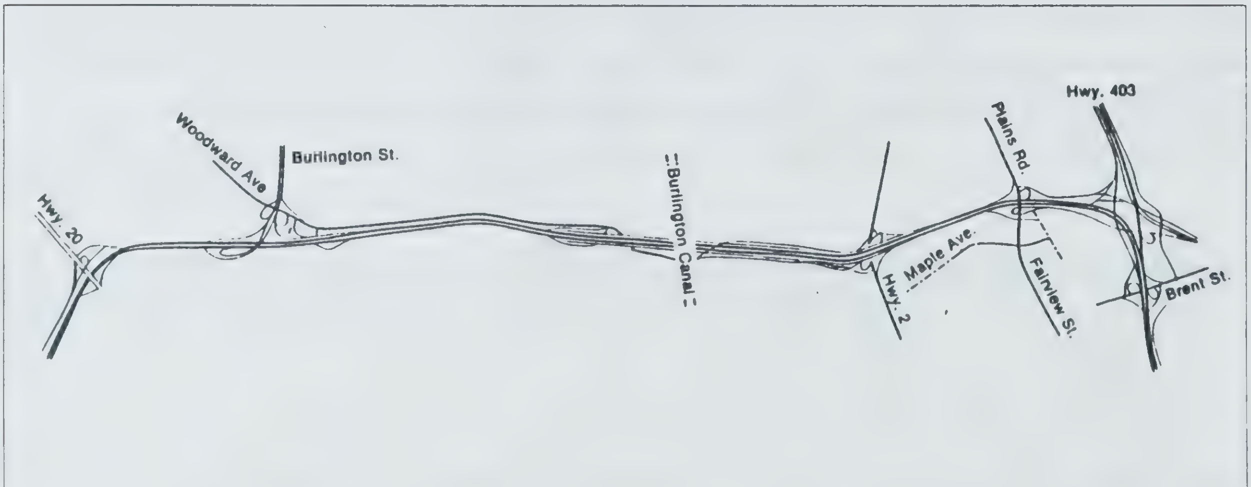


Figure 1b: Hourly Variation of Traffic Volumes as of 1981 (IBI, 1982)

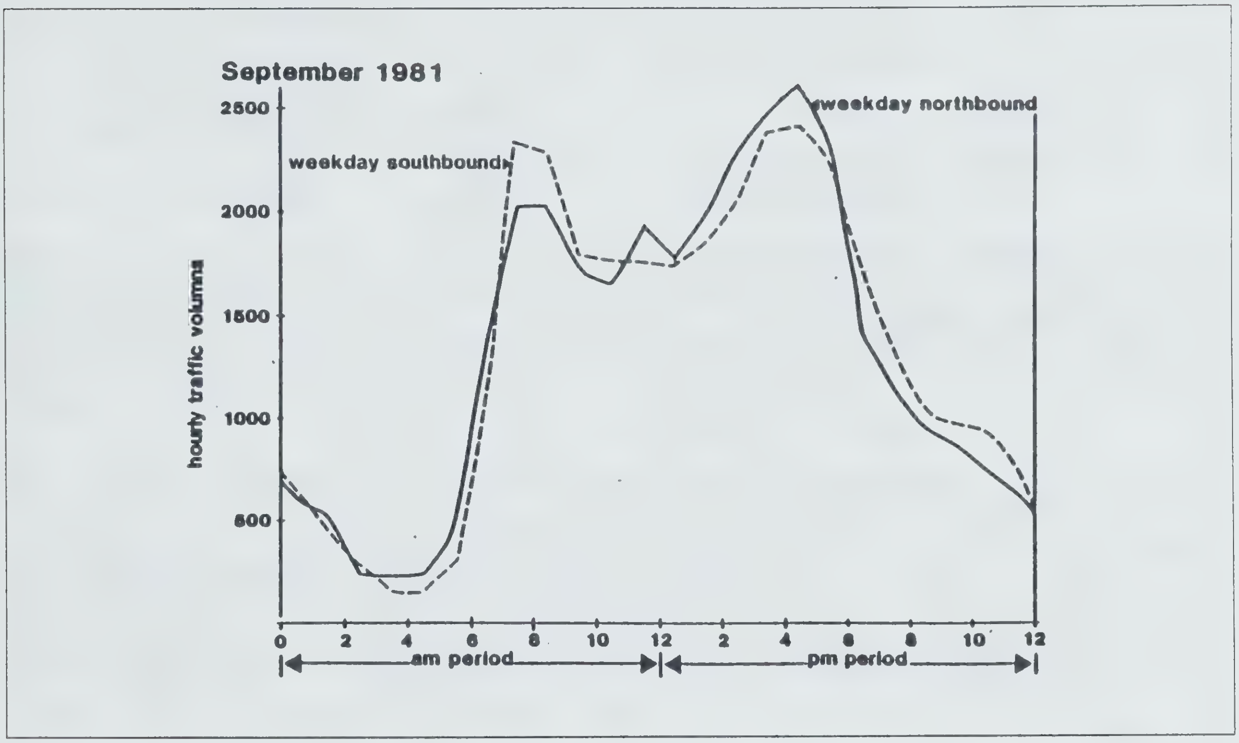


Figure 2: Distribution of Incidents on the Burlington Skyway (IBI, 1982)

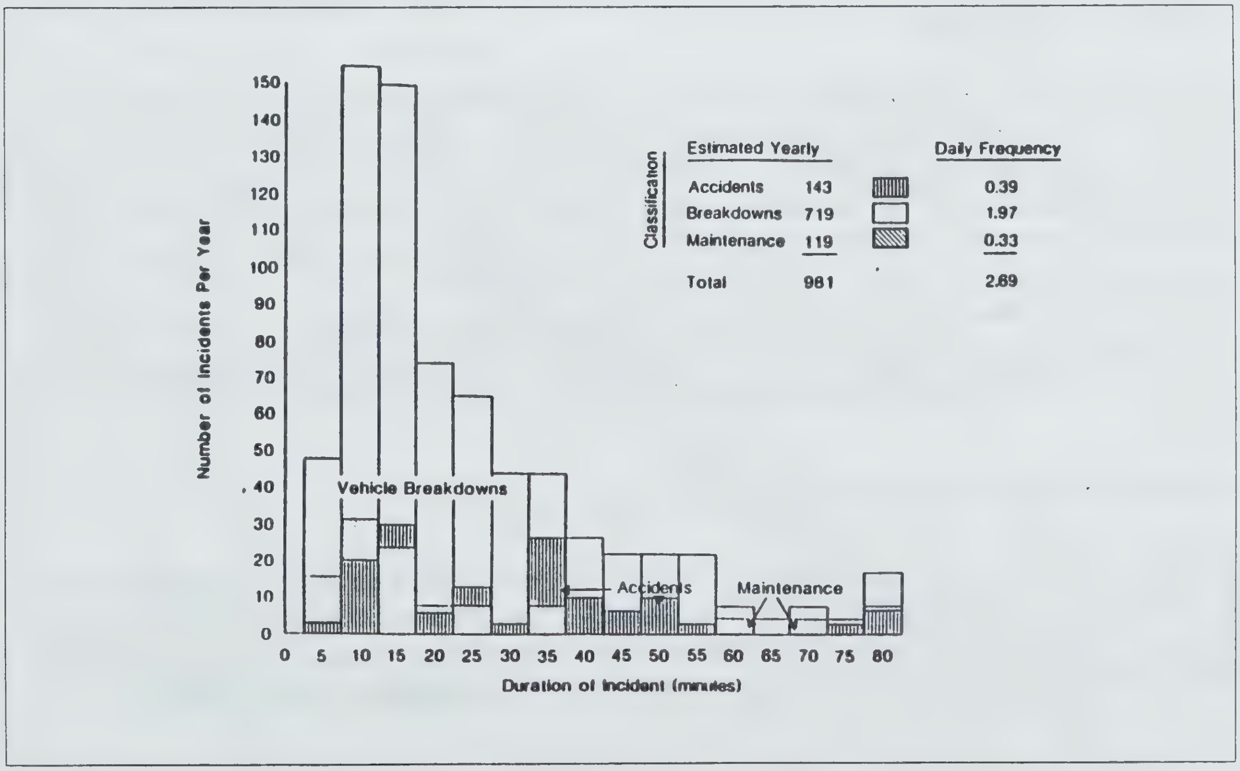


Table 1: Incident and Traffic Statistics for Burlington Skyway (Delsey and Stewart, 1985) and (IBI,1982)

i. Traffic Characteristics (AADT)

Year	AADT	Traffic	% of AADT
1960	17,000 veh/day	-through	27 %
1970	34,600 veh/day	-local	35 %
1980	56,900 veh/day	-external	38 %
2000	100,000 veh/day		

ii. Accident Characteristics

Location	Accident rate
- provincial freeways	0.7 acc./m.v. km
- skyway	2.0-2.3 acc./m.v. km

iii. Incident Characteristics

Incident Type	Frequency	--Lane Closures-- 2 lanes	1 lane	Average Duration (minutes)
- accidents	15 %	6.8%	93.2%	33.8 min
- vehicle breakdowns	72 %	1.0%	99.0%	26.3 min
- maintenance	13 %	-	100.0%	27.1 min

bridge is serving the priority marine traffic, some of the local traffic is better served by utilizing the longer but faster elevated route.

This paper provides a summary of a joint Ministry of Transportation of Ontario-Queen's University study of the Burlington Skyway Corridor with the objective of demonstrating the feasibility and benefits of applying a new traffic simulation model for integrated networks, called INTEGRATION (Van Aerde and Yagar (1988) and Van Aerde et al(1989)). The study first illustrates how the model's input traffic flows can be obtained from Freeway Traffic Management System (FTMS) data already being collected; how a synthetic O-D matrix can be obtained from these flow data; and how the link speed-flow characteristics can be validated. Subsequently, the results of different model runs are discussed in terms of the potential to develop, test and evaluate incident response plans for different severities or durations of incidents.

2. CONFIGURATION OF THE TEST NETWORK

In order to explore the development of incident response plans based on actual traffic flow data from the Burlington Skyway, the southbound Skyway corridor was coded for use in conjunction with the INTEGRATION traffic network simulation model. The model requires 5 basic inputs to describe the network to be analyzed(Van Aerde et al,1989), namely:

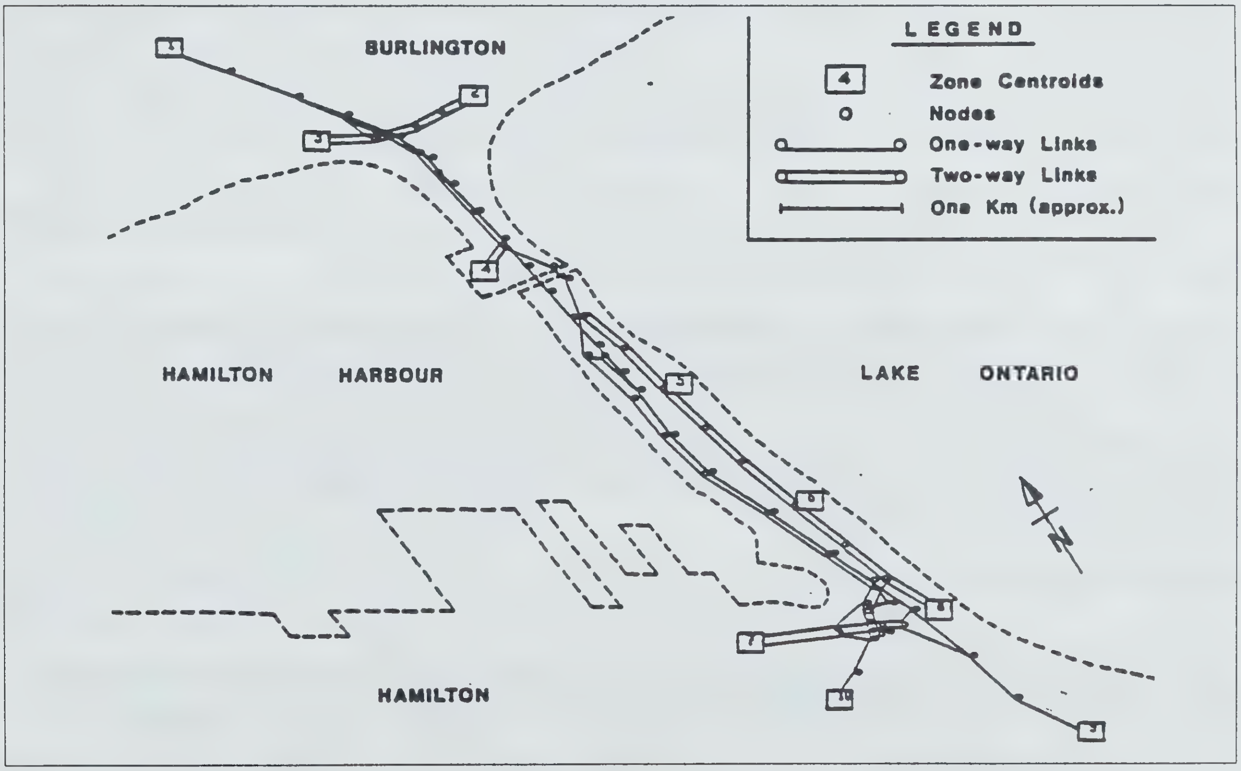
a. a Node coordinates file,
b. a Link descriptor file,
c. a Traffic demand file,
d. a Signal timings file, and
e. an Incident descriptor file.

a. Node coordinates file,

The node coordinates file is used to describe the x-y location of the nodes which are at the start and end of each link in the traffic network. The x-y coordinates are included primarily for purposes of displaying the network and its attributes on the screen during the progress of the simulation, but they can also be utilized to assist in the computation of approximate link lengths.

The node/link representation of the Burlington Skyway in the southbound direction is illustrated in Figure 3. Only the southbound direction was analyzed as it was the only portion of the Skyway that was adequately detectorized at the time of the study. As shown, the network was represented using a total of 73 nodes and 100 links, which had an average length of approximately 200 meters. The entire network was coded using Ontario Ministry of the Environment base maps to obtain the appropriate node coordinates and Ministry of Transportation of Ontario data regarding the location and value of the network attributes.

Figure 3: Network Representation of Burlington Skyway Corridor



b. Link descriptor file,

The link descriptor file provides the attributes of each of the links that join the above nodes. The primary data required in this file are:

- link length (meters)
- number of lanes (integer)
- link free-speed (km/hr.)
- saturation flow per lane (vehicles/hour/lane)
- saturation flow reduction coefficient for congested conditions
  (ratio = congested sat flow / uncongested saturation flow)
- number of traffic signal controlling the link, if any (integer tag number)
- signal phase number (phase during which the signal has effective green)
- link descriptor label(character string)

The derivation of site specific speed-volume and capacity relationships is discussed in detail in later sections of this paper.

c. Traffic demand file,

Traffic demands are applied to the network as a series of origin-demand flow rates which prevail for a user specified time periods.

For example, an O-D demand which remains constant through the entire simulation period can be expressed as a single entry in the demand file which specifies that the hourly demand rate prevails from the start to the end of the simulation. Alternatively, if the demand for a given origin-destination pair changes throughout the simulated time period, it can be specified to the model as a series of entries, one for each time interval during which the demand is approximated to be constant. Finally, if a certain traffic generator only produces trips during a very short peak time period (ie. the end of a baseball game or the closing of an industrial plant), a high demand rate can be specified for a very short time period.

Due to the lack of an adequate survey based origin-destination demand data base, FTMS traffic flow data were utilized to generate a series of synthetic O-D matrices. Each of the O-D matrices were assumed to be valid for 15 minutes at a time and were then sequentially applied to the model to represent the varying traffic demand patterns throughout the peak period. The details of the generation of this sequential origin- destination matrix generation process are discussed in a later section.

d. Signal timings file

The fourth network descriptor identifies the signal control logic that is to be used to set or modify the signal timings at any signalized intersections or ramp meters in the network. Not

only does this file provide the initial timings for each traffic signal, but it also provides the signal timing constraints that cannot be violated by the traffic signal optimizer, if utilized :

- initial, minimum and maximum cycle time (seconds)
- offset of phase 1 relative to absolute clock (seconds)
- number of phases at intersection (integer)
- phase start/end time and associated lost time

During the simulation, all the traffic signals can be operated at different cycle times or at a common cycle time. Alternatively, a cluster of traffic signals can be operated at a common cycle time. Of course, only signals which operate on a common cycle length can be coordinated with each other (except for double cycling).

At the user's choice, signal timings can be updated at user specified intervals based on a moving average of the traffic flows measured on the various approaches to the signal. In this real-time control mode, new cycle times and/or phase times can be calculated using Canadian Capacity Guide methods(ITE,1984) and subject to the forementioned user specified minimum and maximum signal timing parameters. Within the current version of the model, offsets cannot be optimized internally, but an external procedure may be utilized to pre-set these timing parameters.

e. Incident descriptor file.

The final model input consists of an incident descriptor file which indicates to the model the number of incidents that are to be modeled, their severity and duration. Multiple consecutive or concurrent incidents can be modeled using the incident modeller at any location in the network or at any time during the simulation. The incident severity is specified as an effective reduction in the number of lanes, while the incident duration is specified in terms of the start and end time of the incident with reference to the master simulation clock.

f. Routing of traffic

Traffic is routed through the network based on a set of minimum path routing vectors which indicate the turning movements that vehicles should take at each intersection or freeway merge/diverge. These routing vectors can either be computed internally or read in from an external source. The external routing vectors could represent the driver's knowledge of typical peak period traffic conditions, while the internally calculated vectors could represent the routings of drivers which have perfect real-time knowledge of the traffic conditions throughout the network based on CMS data or on information from an in- vehicle route guidance unit. In order to examine the impact of a mixed fleet of driver types, a facility has been added which allows the modeller to specify the fraction of drivers between each O-D pair that route themselves based on the internal vs. external routing vectors.

g. Typical Simulation Run

A typical simulation run starts out when the model reads in the 5 basic data inputs. Subsequently, the specified origin-destination flow rates are decomposed into a series of corresponding individual vehicle departures at prespecified time intervals, and the initial minimum path trees (or routing vectors) are input from an external source and/or generated internally based on the free-flow speeds for every link.

The simulation starts by entering each vehicle into the network at its appropriate departure time. As these vehicles incrementally travel towards their destination, following the turning movements according to their respective minimum paths, they are delayed by any queues, traffic signals or ramp meters. Simultaneously, the effect of any incidents are reflected in the minimum path trees and the signal timings.

As vehicles leave each link, link specific travel times are compiled, while at the conclusion of each trip, O-D specific travel times are also summarized. The former provides system-oriented statistics, as each system link can be studied in turn to determine how it operated. In contrast, the latter provides user-oriented statistics, which indicate the travel characteristics of drivers traveling between a certain origin-destination pair. During the simulation, the calculations and intermediate results of the signal timing updates are summarized, such that the causes of any changes in signal timings can be traced directly.

3. DERIVATION OF LINK SPEED-VOLUME CHARACTERISTICS

The link speed-volume and capacity characteristics of the network were obtained through general reference to the U.S. Highway Capacity Manual(TRB,1985), for the freeway segments, and to the Canadian Capacity Guide(ITE,1984), for the signalized surface streets. In addition, the availability of FTMS data, for the parts of the corridor which were already detectorized, permitted for a direct derivation of some speed- volume relationships from observed field data, as discussed below.

a. Observed Speed-Volume Relationships

At the time of the study, volume, occupancy and speed detectors were in place at a number of sites along the corridor, as indicated in Figure 4a. However, not all of these detectors were always fully operational, such that sufficient speed-volume data could only be obtained for the 4 locations which are illustrated in Figure 4b.

It is important to simultaneously consider all plots in the sequence in order to trace the mechanisms behind these relationships. Figure 5a illustrates the speed-volume behavior upstream of the Burlington Skyway incline. In view of Ontario's 100 km/h speed limit for sections of this type, the speed of traffic can be observed to be very high. Figure 5b illustrates what happens after a high-speed on-ramp adds some additional traffic demand and as the traffic starts moving up the Skyway's grade. The overall speed volume curve has dropped between 5 to 10 km/h., depending upon the traffic volume level. In addition, a maximum lane capacity of slightly more than 1600 veh/hr. (based on 15-minute volumes) can be observed,

Figure 4a: Active Volume and Speed Detector Locations along Southbound Burlington Skyway (Summer/Fall, 1988)

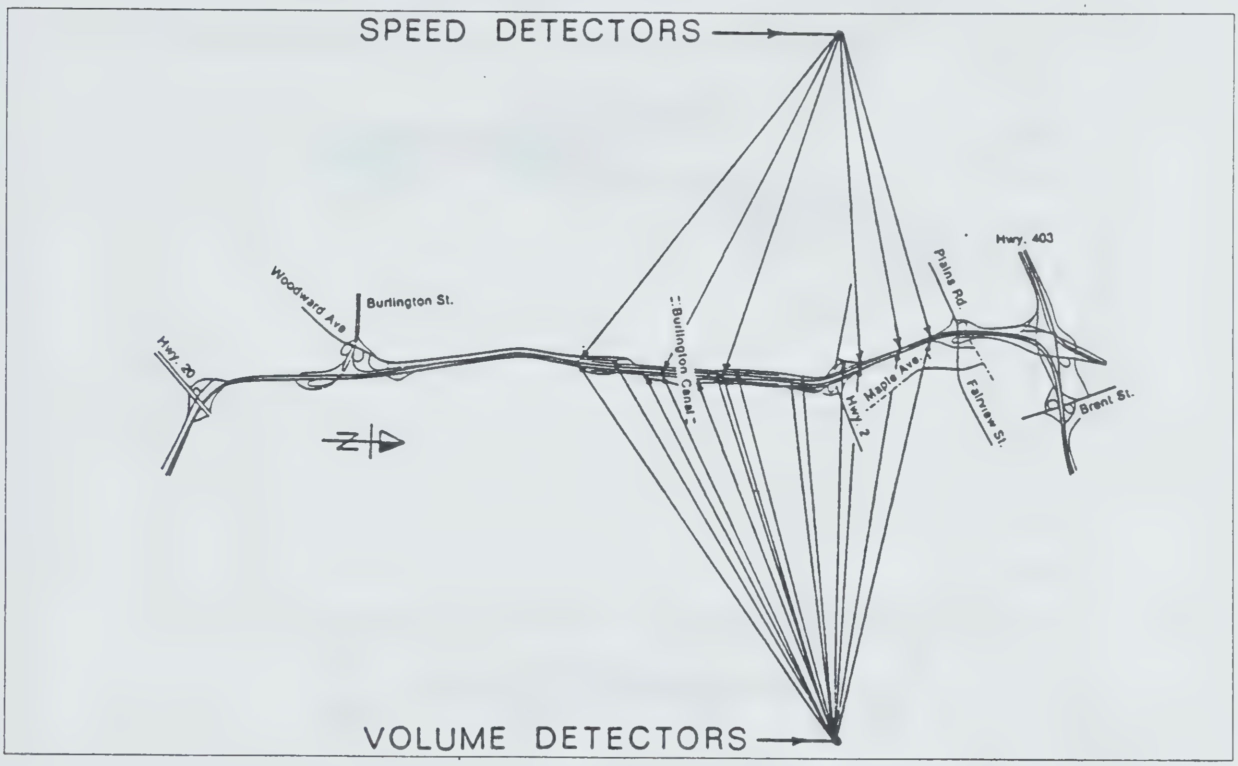


Figure 4b: Speed Detectors Utilized Along Southbound QEW

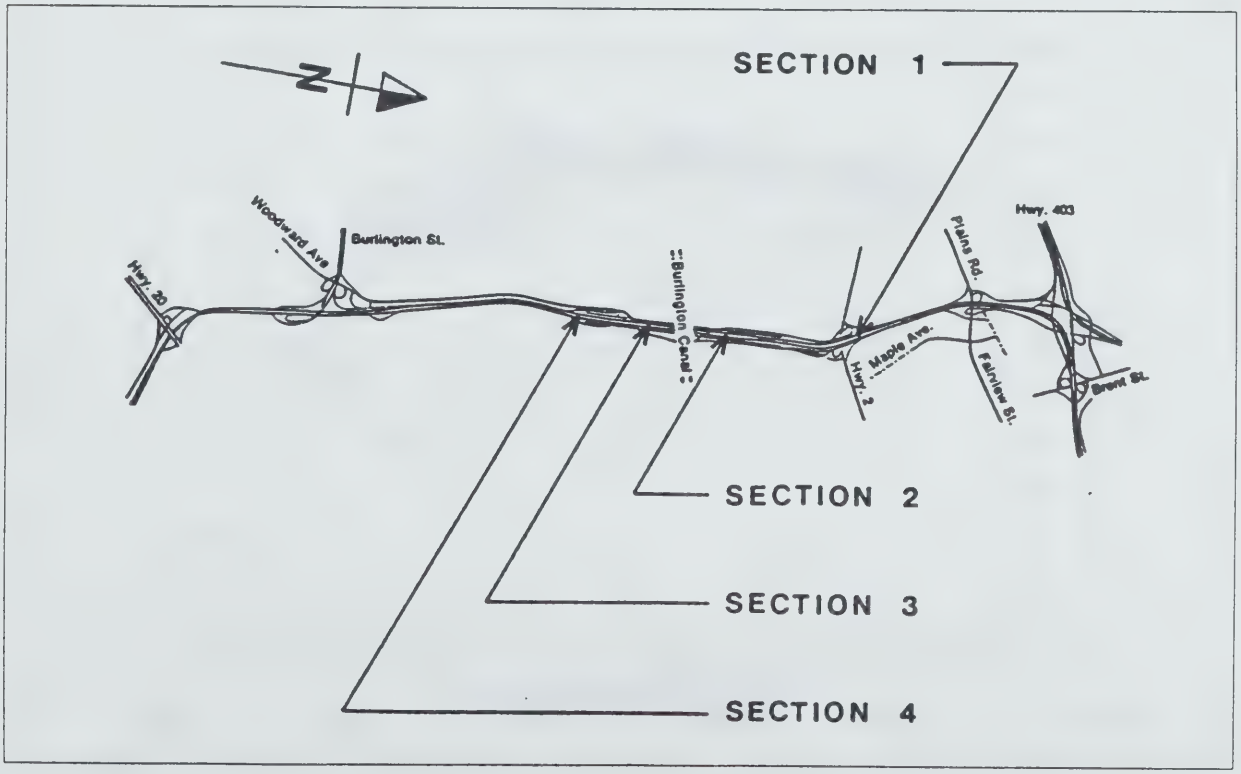


Figure 5a: Speed-Volume Relationship for Section 1

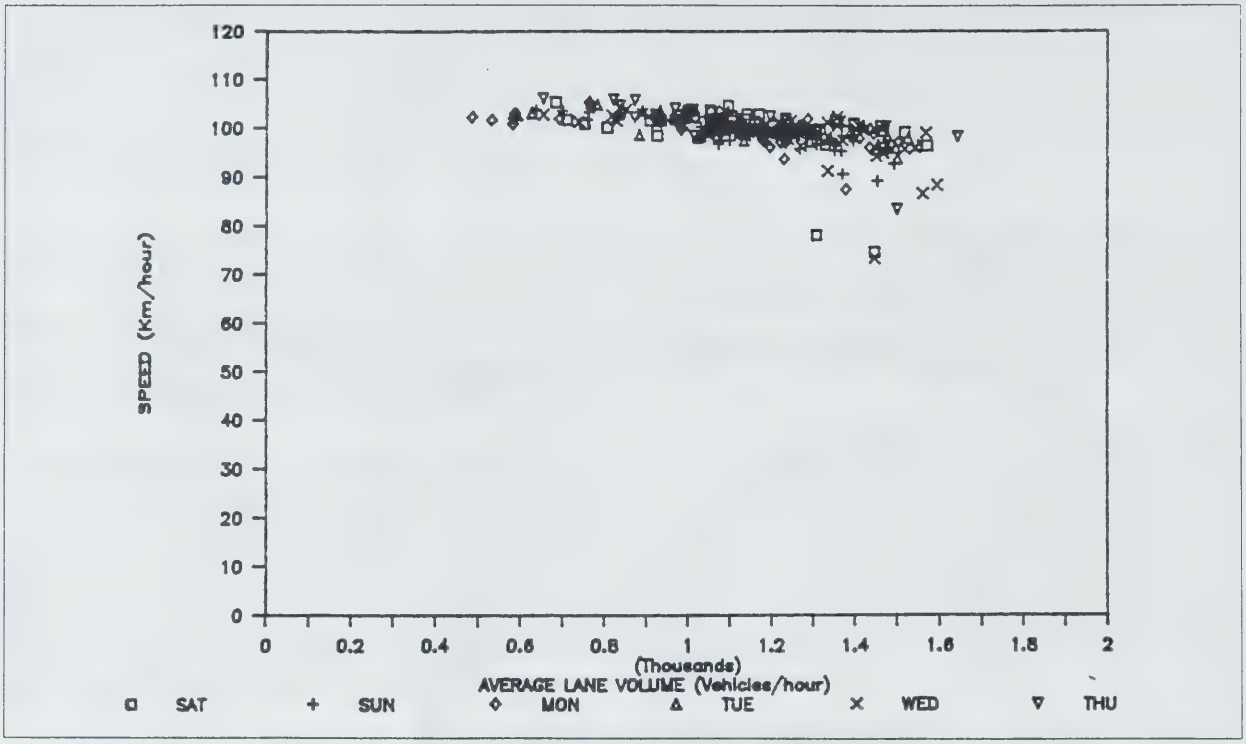


Figure 5b: Speed-Volume Relationship for Section 2

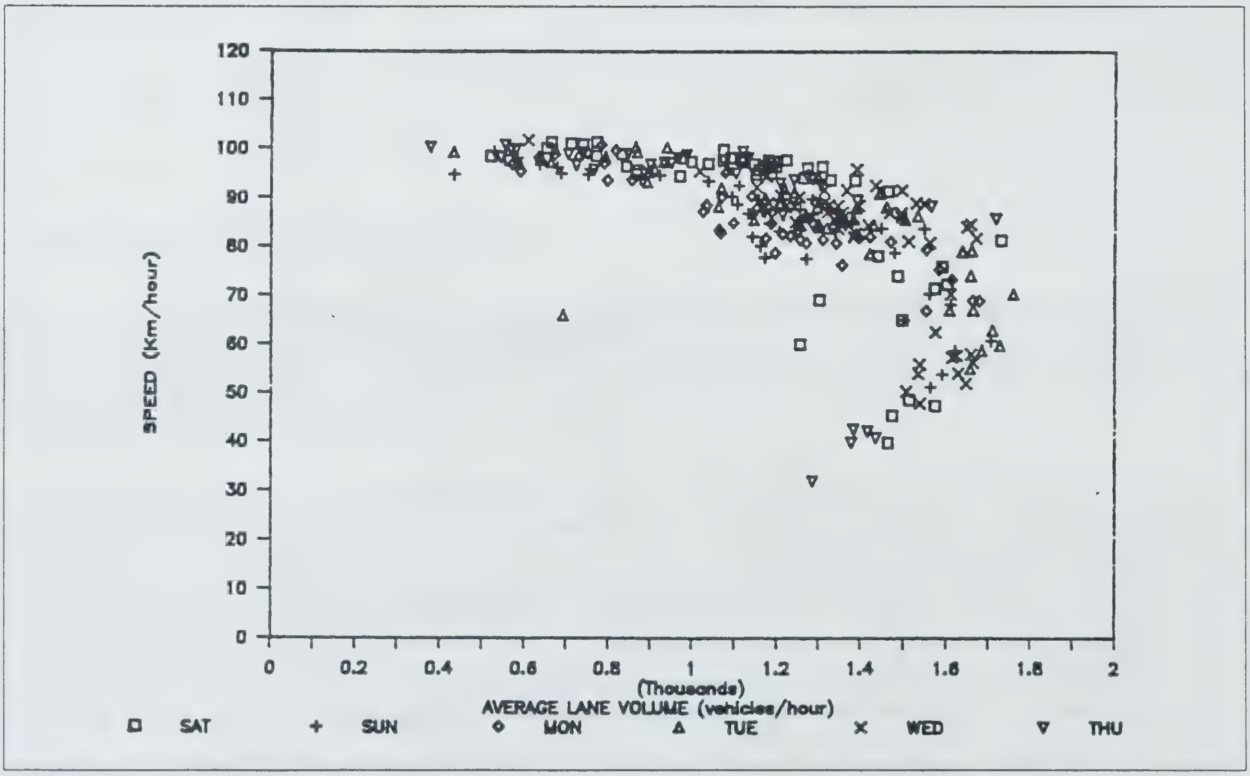


Figure 5c: Speed-Volume Relationship for Section 3

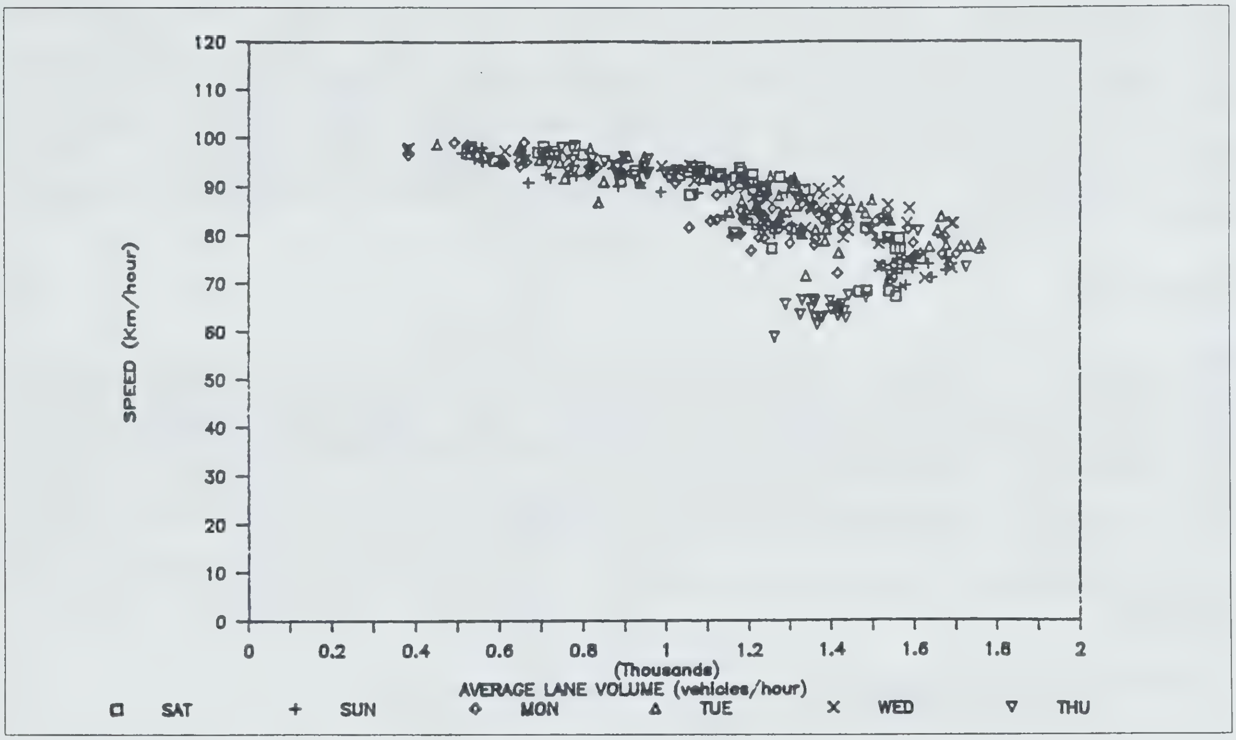
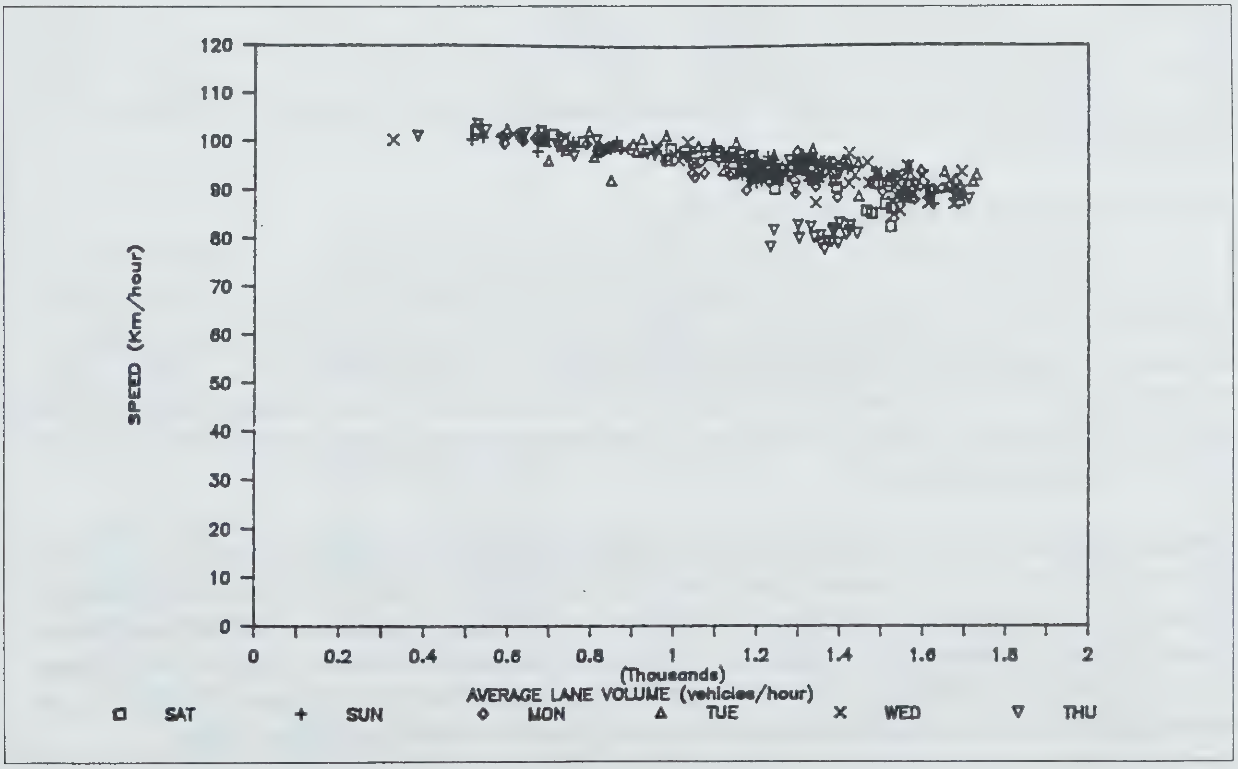


Figure 5d: Speed-Volume Relationship for Section 4



while the backwards bending portion of the curve can be seen to dip to about 40 km/h. at a flow rate of 1400 veh/h.

Figure 5c illustrates the speeds just past the crest of the Skyway. While traffic volumes exceeding the upstream bottleneck value of slightly more than 1600 veh/h. cannot be observed, the backwards bending portion of the speed-volume curve starts to pull up as vehicles start to accelerate on the downwards grade. Finally, Figure 5d illustrates that at the bottom of the grade, the queued vehicles have accelerated sufficiently to achieve speeds comparable to those observed for the uncongested conditions.

b. Discussion

The sequence of speed-volume relationships indicates the potential errors that can arise if one draws premature conclusions when only one speed-volume relationship is analyzed independently of information about up- and/or downstream freeway sections. Specifically, if either Figure 5 c or d were viewed in isolation, incorrect conclusions could be drawn about the ultimate capacity of these downhill sections of the Skyway. Of course, there can even be some doubt as to whether Figure 5b is at the exact location of the bottleneck, but due to the relatively steady grade of the Skyway and the fact that 5b is just short of the crest, this assumption appears reasonable.

4. DERIVATION OF ORIGIN-DESTINATION DEMAND DATA

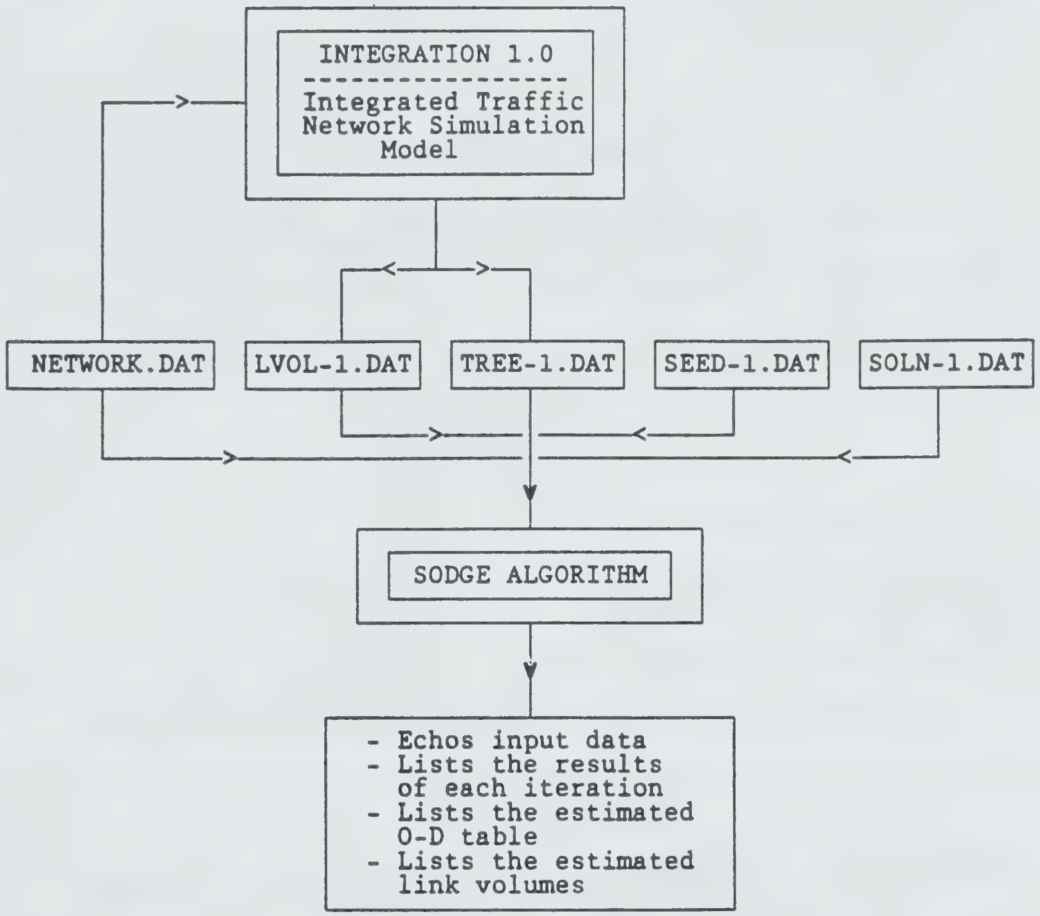
Corridor or network models, such as the INTEGRATION model, require the prevailing traffic demands to be expressed as origin-destination flow rates, rather than as flow rates on each network link. However, direct survey-based measurements of such O-D data were not available for the corridor, especially in view of the fact that separate O-D's needed to be found for each 15-minute period. Consequently, the O-D's for the corridor were estimated using a synthetic O-D generation technique which was designed specifically for use in conjunction with INTEGRATION.

a. Basic Synthetic O-D Generation Techniques

During the late 1970's a number of procedures were developed to derive synthetic O-D matrices from link counts and optionally an approximate seed matrix. Such models minimized information or maximized entropy within the matrix in order to determine which of the numerous possible origin-destination matrices, is the most likely one. Models, such as Van Zuylen and Willumsen's(1980) ME2, have since been successfully applied to estimate O-D matrices for planning purposes.

A revised ME2 algorithm (Van Zuylen,1981) was implemented as a new computer program by Noxon(1988) to allow all model inputs to be compatible with the INTEGRATION simulation model. The resulting program is referred to as SODGE (Synthetic Origin-Destination Generator) and is illustrated in Figure 6. It involves the use of network data and minimum path trees from the INTEGRATION model in conjunction with Burlington FTMS data to back-calculate the most likely O-D matrix for one 15 minute time period at a time.

Figure 6: Combined INTEGRATION/SODGE Derivation of Synthetic O-D's



LVOL-1.DAT:	Contains the link volumes generated by INTEGRATION 1.0 for the time interval being analyzed.
TREE-1.DAT:	Contains the minimum path trees generated by INTEGRATION 1.0 for the time interval being analyzed.
NETWORK.DAT:	Describes the network used both by SODGE and INTEGRATION 1.0.
SEED-1.DAT:	Contains the seed matrix (real or default) for the time interval being analyzed.
SOLN-1.DAT:	Contains the actual solution matrix (if known) for the time interval being analyzed.

Figure 7: On-Line Estimation of Synthetic O-D's from FTMS Data

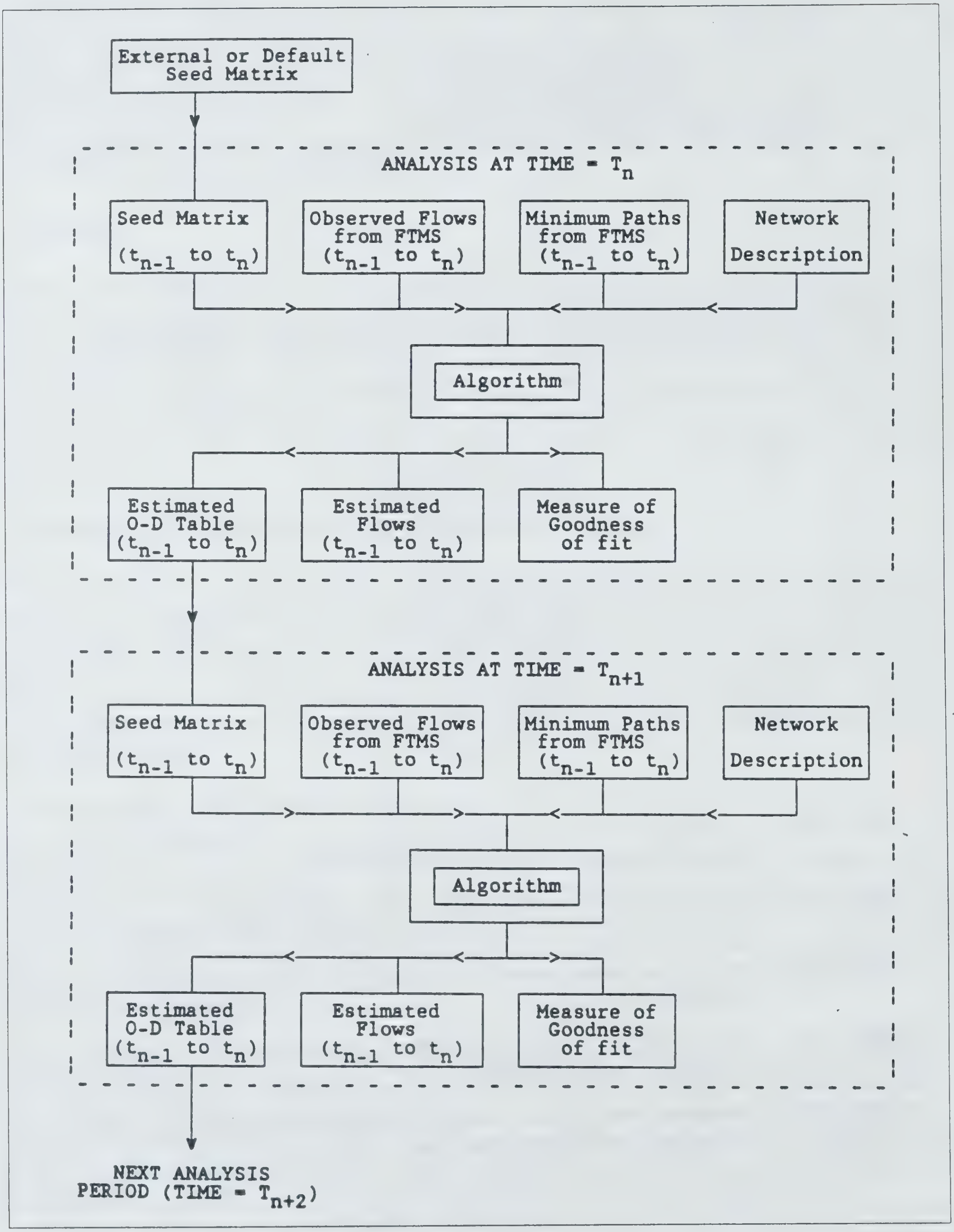


Table 2a: Synthetic Origin-Destination Matrix for 7:00-7:15 AM

Orig down	Destinations across										
	1	2	3	4	5	6	7	8	9	10	SUMS
1	0	64	64	139	12	12	609	179	858	118	2056
2	0	0	67	45	4	4	36	54	26	18	253
3	0	67	0	45	4	4	36	54	26	9	244
4	0	0	0	0	6	6	0	329	0	0	341
5	0	0	0	0	0	0	21	0	24	5	51
6	0	0	0	0	0	0	21	33	176	5	236
7	0	0	0	0	0	33	0	33	555	120	742
8	0	0	0	0	0	33	21	0	0	5	60
9	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0
SUMS	0	131	131	228	26	93	745	682	1665	281	3982

Table 2b: Synthetic Origin-Destination Matrix for 7:15-7:30 AM

Orig down	Destinations across										
	1	2	3	4	5	6	7	8	9	10	SUMS
1	0	86	86	241	22	22	704	168	1165	174	2665
2	0	0	158	50	5	5	51	62	43	32	405
3	0	158	0	50	5	5	51	62	43	16	389
4	0	0	0	0	15	15	0	422	0	0	451
5	0	0	0	0	0	0	26	0	32	19	76
6	0	0	0	0	0	0	26	78	122	19	244
7	0	0	0	0	0	78	0	78	743	80	978
8	0	0	0	0	0	78	26	0	0	19	122
9	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0
SUMS	0	243	243	340	46	201	882	868	2148	358	5330

Table 2c: Synthetic Origin-Destination Matrix for 7:30-7:45 AM

Orig down \ Destinations across	1	2	3	4	5	6	7	8	9	10	SUMS
1	0	106	106	413	21	21	751	23	1378	68	2884
2	0	0	292	18	1	1	104	16	97	24	553
3	0	292	0	18	1	1	104	16	97	12	541
4	0	0	0	0	15	15	0	487	0	0	518
5	0	0	0	0	0	0	68	0	80	102	250
6	0	0	0	0	0	0	68	144	195	102	510
7	0	0	0	0	0	144	0	144	843	210	1341
8	0	0	0	0	0	144	68	0	0	102	314
9	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0
SUMS	0	398	398	450	38	327	1162	830	2690	619	6911

Table 2d: Synthetic Origin-Destination Matrix for 7:45-8:00 AM

Orig down \ Destinations across	1	2	3	4	5	6	7	8	9	10	SUMS
1	0	110	110	554	12	12	776	138	1710	165	3588
2	0	0	707	54	1	1	92	82	103	50	1090
3	0	707	0	54	1	1	92	82	103	25	1065
4	0	0	0	0	15	15	0	584	0	0	615
5	0	0	0	0	0	0	132	0	96	100	328
6	0	0	0	0	0	0	132	348	134	100	715
7	0	0	0	0	0	348	0	348	726	340	1763
8	0	0	0	0	0	348	132	0	0	100	580
9	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0
SUMS	0	817	817	663	30	727	1356	1583	2872	880	9743

Table 3a: Synthetic Origin-Destination Matrix for 8:00-8:15 AM

Orig down	Destinations across 1	2	3	4	5	6	7	8	9	10	SUMS
1	0	34	34	380	18	18	696	70	1573	118	2942
2	0	0	407	4	0	0	108	55	124	47	745
3	0	407	0	4	0	0	108	55	124	23	721
4	0	0	0	0	19	19	0	313	0	0	352
5	0	0	0	0	0	0	91	0	64	81	236
6	0	0	0	0	0	0	91	200	149	81	520
7	0	0	0	0	0	200	0	200	674	231	1304
8	0	0	0	0	0	200	91	0	0	81	372
9	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0
SUMS	0	441	441	388	38	438	1185	892	2709	662	7192

Table 3b: Synthetic Origin-Destination Matrix for 8:15-8:30 AM

Orig down	Destinations across 1	2	3	4	5	6	7	8	9	10	SUMS
1	0	106	106	294	13	13	730	118	1675	111	3167
2	0	0	505	84	0	0	70	57	82	27	824
3	0	505	0	84	0	0	70	57	82	13	810
4	0	0	0	0	23	23	0	512	0	0	557
5	0	0	0	0	0	0	71	0	84	56	212
6	0	0	0	0	0	0	71	248	96	56	471
7	0	0	0	0	0	248	0	248	684	120	1301
8	0	0	0	0	0	248	71	0	0	56	376
9	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0
SUMS	0	611	611	461	36	532	1085	1240	2702	440	7718

Table 3c: Synthetic Origin-Destination Matrix for 8:30-8:45 AM

Orig down \ Destinations across	1	2	3	4	5	6	7	8	9	10	SUMS
1	0	124	124	202	16	16	810	39	1831	49	3213
2	0	0	360	255	0	0	5	1	6	1	628
3	0	360	0	255	0	0	5	1	6	0	628
4	0	0	0	0	30	30	0	272	0	0	332
5	0	0	0	0	0	0	41	0	40	53	135
6	0	0	0	0	0	0	41	177	76	53	348
7	0	0	0	0	0	177	0	177	665	100	1118
8	0	0	0	0	0	177	41	0	0	53	271
9	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0
SUMS	0	484	484	712	46	400	945	668	2623	310	6672

Table 3d: Synthetic Origin-Destination Matrix for 8:45-9:00 AM

Orig down \ Destinations across	1	2	3	4	5	6	7	8	9	10	SUMS
1	0	130	130	232	11	11	659	133	1570	48	2925
2	0	0	298	3	0	0	61	51	77	15	506
3	0	298	0	3	0	0	61	51	77	0	492
4	0	0	0	0	15	15	0	237	0	0	267
5	0	0	0	0	0	0	19	0	32	13	64
6	0	0	0	0	0	0	19	147	43	13	221
7	0	0	0	0	0	147	0	147	659	100	1053
8	0	0	0	0	0	147	19	0	0	13	178
9	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0
SUMS	0	429	429	239	26	319	839	766	2458	200	5705

b. Sequential O-D Matrix Generation using SODGE

However, as the accuracy of the estimated O-D matrix and the time required to find this estimate are highly sensitive to the accuracy of the initial seed matrix, a modification was introduced into the estimation process (Van Aerde,Voss and Noxon,1989). This modification employed the O-D matrix, which was estimated for the previous time period, as the on-line seed for the next time period's O-D calculations, as illustrated in Figure 7. During these calculations, the previous period's matrix is fine-tuned in view of any changes in link flows that have been observed from the FTMS detectors. The overall procedure was tested extensively using Burlington Skyway data, and sensitivities to network transients and the quality of the seed matrix were established (Van Aerde, Voss and Noxon,1989).

The above technique was applied to determine a sequence of synthetic 15- minute O-D matrices for an entire 24 hour weekday. The results of this analysis are illustrated in Tables 2 a,b,c and d, and Tables 3 a,b,c and d, which list the prevailing matrices between 7:00 and 9:00 AM. These matrices illustrate not only a general scaling of the matrix during the peak, but also indicate a structural shift in the relative magnitudes of the O-D matrices' cell entries throughout the morning peak.

5. ANALYSIS OF INCIDENT IMPACTS AND INCIDENT RESPONSE PLANS

The above speed-volume and origin-destination data were utilized as inputs to an analysis of the Burlington Skyway network for 3 different incident scenarios, namely a single lane blockage on the uphill section of the Skyway for 10, 20 or 30 minutes. In addition, the scenario where no incident takes place was analyzed to establish a base condition. Furthermore, in order to estimate the impact of different response plans, combinations of situations with real-time traffic re-routing and/or real-time signal retiming were also considered.

a. Analysis of Aggregate Total Travel Times

The consequences of incidents of various durations and the corresponding impacts of different incident response measures are illustrated in Table 4. It shows not only the changes in travel times (minutes/trip) for 6 representative origin-destination trips, but also summarizes the total travel time for all drivers in the network (vehicle-hours).

The first 4 entries in Table 4 indicate the impact of signal retimings and traffic rerouting for the non-incident situation. If the signal timings are not recalculated in real time and the routings are kept constant throughout the analysis period, the total trip time for all vehicles in the network is 1316 veh-hrs. When signal timings are allowed to be updated in real-time (every 5 minutes) in response to the observed traffic volumes, the total travel time decreases significantly to a value of 1208 veh-hrs. Alternatively, if the timings were kept constant, but the routings were updated every 5 seconds throughout the peak period, the travel times only dropped to 1295 veh-hrs. Finally, when both real-time re-routing and signal re-timing were permitted, the total travel time dropped to 1192 veh-hrs.

Table 4: Aggregate Total Travel Times for Different Incidents/Controls

INCIDENT STATUS	SIGNAL UPDATE ?	TREE UPDATE ?	AVERAGE TRIP TIME (min) FOR 6 ORIGIN - DESTINATION PAIRS (1-7)	(1-9)	(2-7)	(2-9)	(3-7)	(3-9)	TOTAL TRIP TIME IN VEHICLE HOURS	RELATIVE TIMES TO: A (%)	B (%)
No Incident	N	N	8.1	8.6	9.4	9.8	12.9	13.8	1316.62	100	100
	Y	N	8.1	8.6	9.4	9.9	9.5	9.9	1208.54	92	92
	N	Y	8.0	8.1	9.8	9.7	13.2	13.7	1295.33	96	96
	Y	Y	7.8	8.1	9.5	9.8	9.6	9.8	1192.13	91	91
10 min. Incident	N	N	9.3	9.8	12.8	13.4	15.8	17.0	1460.64	111	100
	Y	N	9.3	9.9	13.6	14.4	13.8	14.6	1377.85	105	94
	N	Y	8.0	8.2	9.9	9.8	13.4	13.8	1305.18	99	89
	Y	Y	7.8	8.2	9.5	9.8	9.6	9.9	1195.51	91	82
20 min. Incident	N	N	10.4	11.1	24.2	25.9	22.0	24.3	1781.93	135	100
	Y	N	10.4	11.1	24.6	26.6	22.2	23.7	1755.22	133	99
	N	Y	8.4	8.6	10.5	10.6	13.9	14.3	1359.83	103	76
	Y	Y	8.0	8.3	9.8	10.1	9.8	10.2	1216.37	92	68
30 min. Incident	N	N	12.1	13.0	21.2	22.4	18.4	20.4	1826.41	139	100
	Y	N	12.1	13.0	20.5	22.2	19.0	20.1	1751.10	133	96
	N	Y	9.0	9.1	12.2	12.1	15.2	15.6	1436.65	109	79
	Y	Y	8.1	8.5	10.0	10.3	10.1	10.5	1232.93	94	67

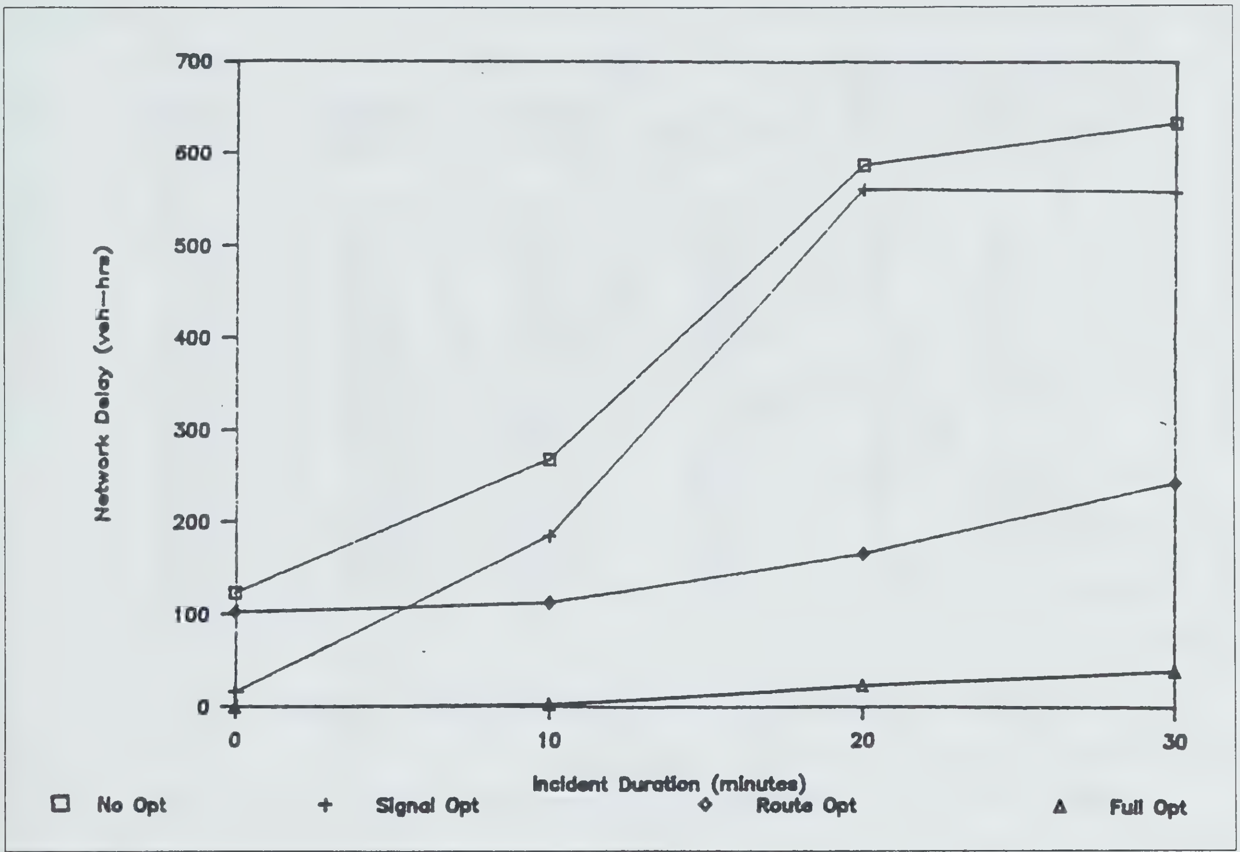
note: 1) Relative Time A: 100% = no incident, no re-routing and no re-timing.
2) Relative Time B: 100% = incident, no re-routing and no re-timing.

Table 5: Increases in Travel Delay to Different Incident Responses

Sig. Opt.	Route Opt.	No Incident	10 min Incident	20 min Incident	30 min Incident
N	N	124.49	268.51	589.80	634.28
Y	N	16.41	185.72	563.09	558.97
N	Y	103.20	113.05	167.70	244.52
Y	Y	0.00	3.38	24.24	40.80

Note: All of the above increases in vehicle hours of travel time are expressed relative to the values for the non-incident situation with full re-routing/signal timing optimization.

Figure 8: Travel Time Reductions for Different Incident Responses



b. Implications

This implies that for non-incident conditions, the effect of providing drivers with continuously updated routing information is marginal (ie. 1316 veh-hrs vs. 1295 veh-hrs = 1.6% reduction), while the re-timing of traffic signals, to follow the growth and decay in traffic volumes on the signalized approaches, provided a relatively significant decrease in travel time (ie. 1316 veh-hrs vs. 1208 veh-hrs = 8.2 % reduction).

When incidents of increasing severity are introduced into the network, the total travel time increases significantly, especially when no response plan is implemented. Table 5 and Figure 8 summarize the total and average increases in travel time for the various incident durations. As shown, the re-timing of traffic signals has a relatively constant effect of reducing travel times by about 100 veh-hrs. However, the re-routing of traffic results in an increasingly larger reduction in travel time as it manages to divert an increasing amount of traffic away from the bottleneck towards other network links where spare capacity exists. When this re-routing takes place, the incremental savings due to simultaneous signal re-timing appear to remain relatively constant.

Table 6: Time-Series of O-D Travel Times for Specific O-D's

O-D PAIR	Start Time (min)	End Time (min)	No Incident	10 min. Incident	20 min. Incident	30 min. Incident
1-9	0	15	7.22	7.22	7.22	7.22
	15	30	7.87	7.87	7.87	7.87
	30	45	8.10	8.28	8.28	8.28
	45	60	8.52	8.58	9.37	9.37
	60	75	8.30	8.32	8.38	8.53
	75	90	8.28	8.35	8.40	8.40
	90	105	8.17	8.22	8.17	8.12
	105	120	8.10	7.93	8.08	8.05
2-7	0	15	8.00	8.00	8.00	8.00
	15	30	8.42	8.42	8.42	8.42
	30	45	8.63	8.77	8.77	8.77
	45	60	9.30	9.37	10.10	10.10
	60	75	8.98	9.00	8.93	9.18
	75	90	8.97	9.00	9.02	9.05
	90	105	8.67	8.58	8.65	8.63
	105	120	8.52	8.55	8.52	8.52

Figure 9a: Time-Series of O-D Travel Times for Zones 1-9

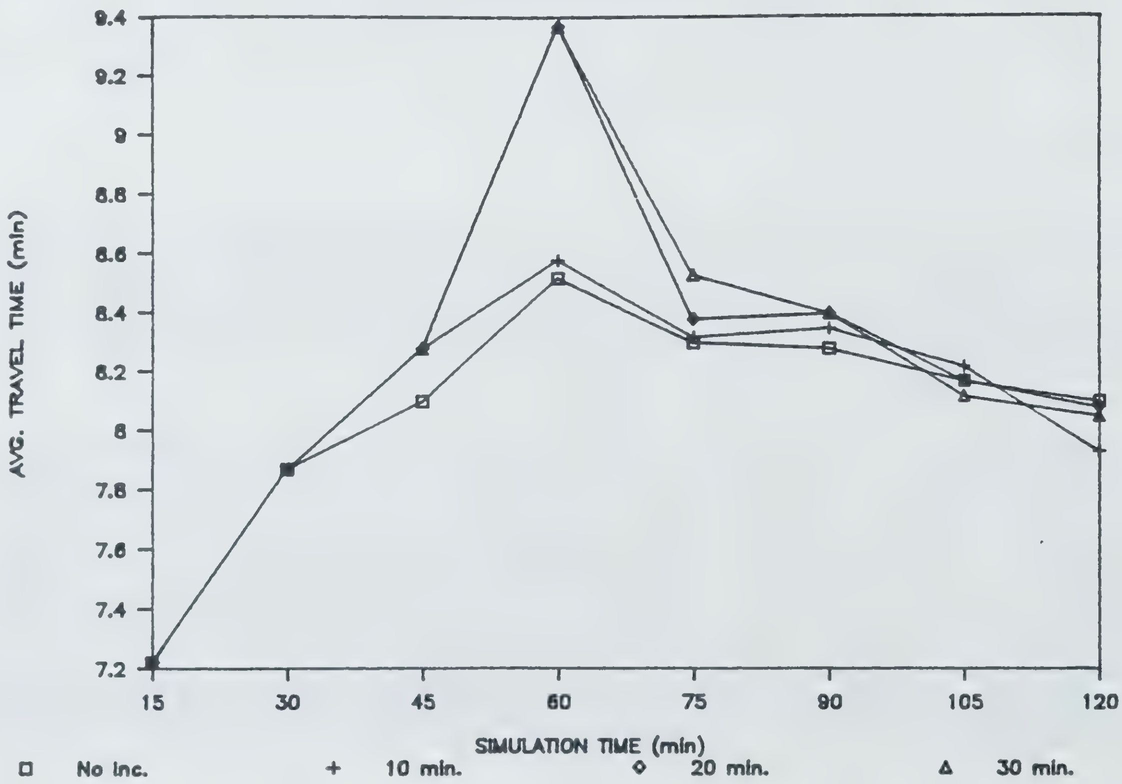
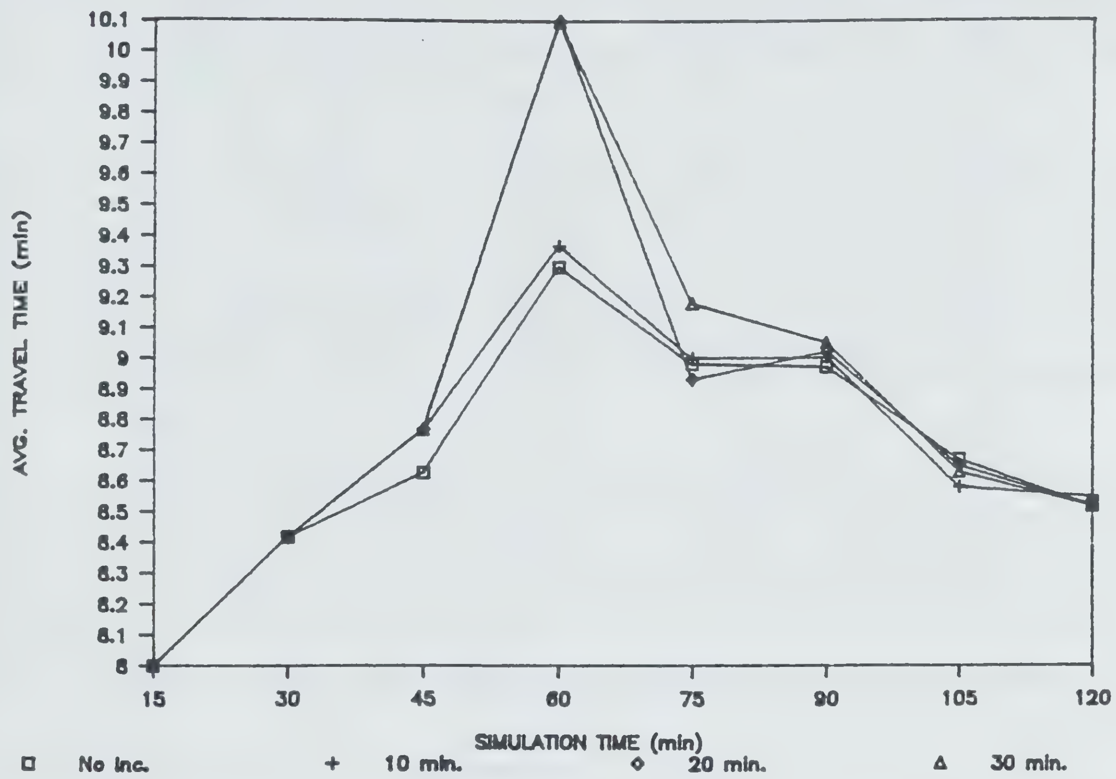


Figure 9b: Time-Series of O-D Travel Times for Zones 2-7



c. Incident and Response Plan Impact on Specific O-D's

The impacts on travel times between 2 separate O-D pairs are summarized in Table 6 and illustrated in Figures 9 a and b. These data represent instantaneous travel time estimates between various O-D pairs at 15 minute intervals during the analysis period.

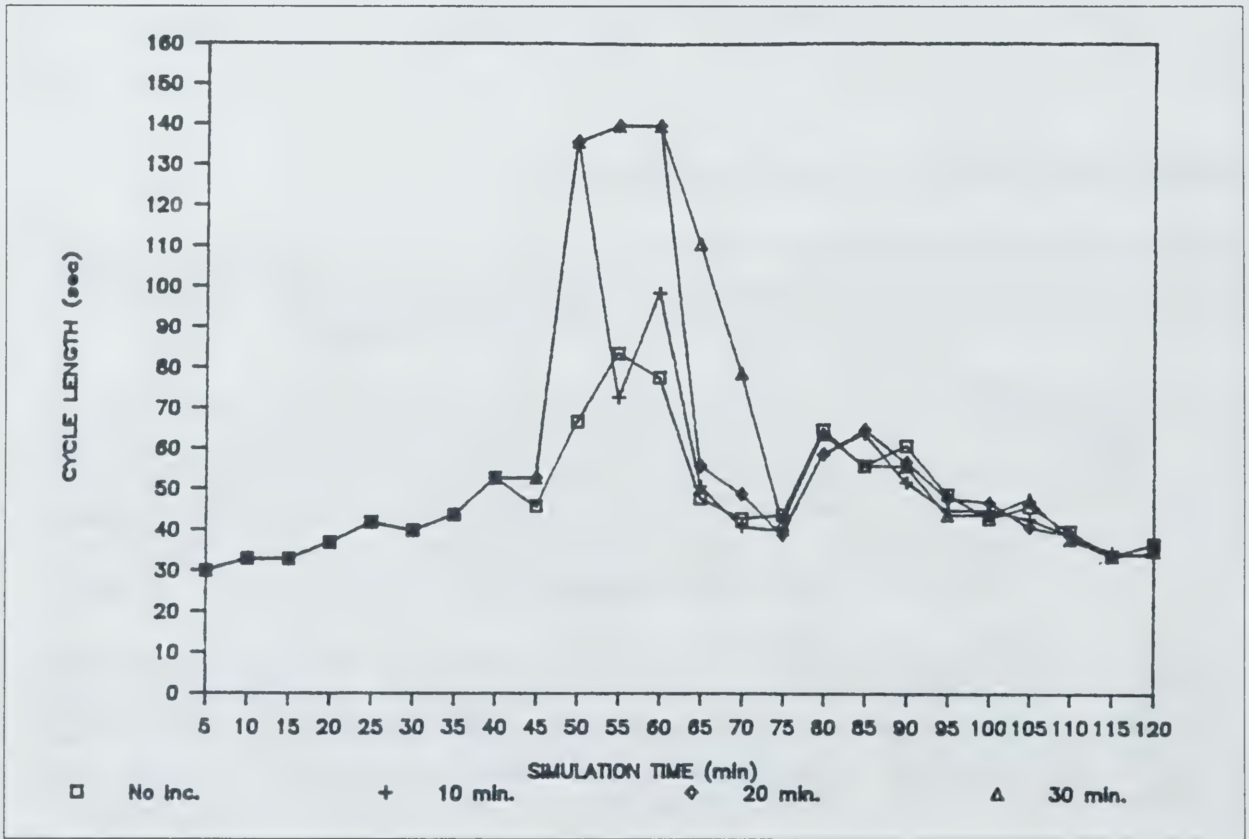
As shown, the travel times for both O-D pairs increase only gradually during the analysis period and peak approximately 1 hour into the simulation (ie. at 8:00 AM). However, as shown in Figures 9 a and b, the travel times increase significantly (by more than 1 minute) when the incident, which started at 7:41 minutes, is still present at 8:00 AM or 1 hour into the simulation (the 20 and 30 minute incidents). In each case, the increase in travel time has virtually disappeared by 8:15 AM, when even the 30-minute incident has been cleared for 4 minutes.

The reasons for the short-lived residual impact of the incident is the relatively small capacity deficit which existed when the 1 lane was blocked. Consequently, only a short queue was present at the bottleneck, especially when much of the excess demand was rerouted. This short queue could quickly be served, when the lane blockage was removed, such that the corresponding travel times were virtually immediately restored to their pre-incident values.

Table 7: Changes in Signal Timings at Traffic Signal 5 on Service Road

SIM. TIME	NO INCIDENT			10 min INCIDENT			20 min INCIDENT			30 min INCIDENT		
	CYC.	PHASE		CYC.	PHASE		CYC.	PHASE		CYC.	PHASE	
min.	TIME sec.	1 sec.	2 sec.	TIME sec.	1 sec.	2 sec.	TIME sec.	1 sec.	2 sec.	TIME sec.	1 sec.	2 sec.
5	30	9	11	30	9	11	30	9	11	30	9	11
10	33	9	14	33	9	14	33	9	14	33	9	14
15	33	9	14	33	9	14	33	9	14	33	9	14
20	37	9	18	37	9	18	37	9	18	37	9	18
25	42	13	19	42	13	19	42	13	19	42	13	19
30	40	11	19	40	11	19	40	11	19	40	11	19
35	44	11	23	44	11	23	44	11	23	44	11	23
40	53	18	25	53	18	25	53	18	25	53	18	25
45	46	13	23	53	19	24	53	19	24	53	19	24
50	67	23	34	136	64	62	136	64	62	136	64	62
55	84	33	41	73	26	37	140	67	63	140	67	63
60	78	29	39	99	41	48	140	68	62	140	68	62
65	48	18	20	51	21	20	56	24	22	111	64	37
70	43	17	16	41	15	16	49	22	17	79	46	23
75	44	19	15	40	16	14	39	15	14	42	17	15
80	65	26	29	59	22	27	59	22	27	64	25	29
85	56	18	28	64	23	31	65	24	31	56	18	28
90	61	22	29	52	16	26	57	19	28	56	18	28
95	49	21	18	45	18	17	48	20	18	44	17	17
100	43	18	15	45	19	16	47	21	16	44	19	15
105	46	22	14	43	19	14	41	17	14	48	23	15
110	40	18	12	39	17	12	39	17	12	38	16	12
115	34	14	10	35	14	11	34	13	11	34	14	10
120	37	16	11	34	13	11	35	14	11	37	16	11

Figure 10: Changes in Signal Timings atTraffic Signal 5 on Service Road



d. Signal Timing Re-Calculations

Throughout the simulation, signal timings were updated at 5 minute intervals based on a moving average of upstream approach traffic volumes. Each intersection was optimized in isolation, such that different cycle times and phase splits could be computed, without regard for any coordination of off-sets between the adjacent intersections.

The overall travel time impacts of the re-timing at all intersections in the network were already indicated in Table 1. In addition, the specific time series of signal timings for the various incident scenarios at signal 5 (located halfway along the arterial diversion route) are provided in Table 7 and Figure 10. As shown, the cycle time for non-incident conditions increases gradually during the analysis period and reaches a peak at 8:00 AM of about 80 seconds, when the traffic flows peak as well. However, when an incident occurs, which diverts considerably more traffic to the surface route, the cycle time is shown to increase rapidly to the maximum value of 140 seconds.

For the 10 minute incident, the signal timings return quickly to normal, approximately 4 minutes after the incident has been cleared (7:55 AM or 55 minutes into simulation). Of course, for the 20 and 30 minute incident, the signal timings remain at their maximum levels for longer periods, but again they quickly return to normal, shortly after the incident is cleared. It is interesting to note that even for the 30 minute incident, the signal does not operate at its maximum value for the entire period, as the tail end of the incident coincides with a general reduction in traffic demand after its peak has been reached at about 8 AM.

6. INTEGRATION WITH ROUTE GUIDANCE SYSTEM

The above analysis of different routing-based response plans assumed that a mechanism existed to notify drivers in real-time of the changes in traffic conditions throughout the network. This, of course, is only possible if a fully integrated driver information system exists which efficiently distributes accurate routing information to the drivers. A comprehensive system which can serve this function, called Q-Route, has been developed at Queen's University. As its features and limitations have already been discussed in detail in Van Aerde and Blum(1988) and in Blum and Van Aerde(1989), this section focuses on describing how the system can be applied within the Burlington Skyway corridor.

a. Q-Route Concept

The Q-ROUTE concept involves the provision of comprehensive route guidance information to drivers based on the routing vectors which are generated by a traffic control model such as INTEGRATION. Such routing vectors can reflect the traffic conditions, controls, congestion and any incidents on the network, and are generated automatically as part of the simulation process. Not only does this INTEGRATION to Q-ROUTE link allow the routing vectors to be generated based on the real-time behavior of the traffic network, but it also allows the INTEGRATION model to track the impact of the routing system on the performance of the traffic network. Consequently, the benefits of mutually consistent controls and routings can be analyzed throughout the network and for each subpopulation of drivers.

Figure 11a: Q-Route Macro Network for the Greater Toronto Area

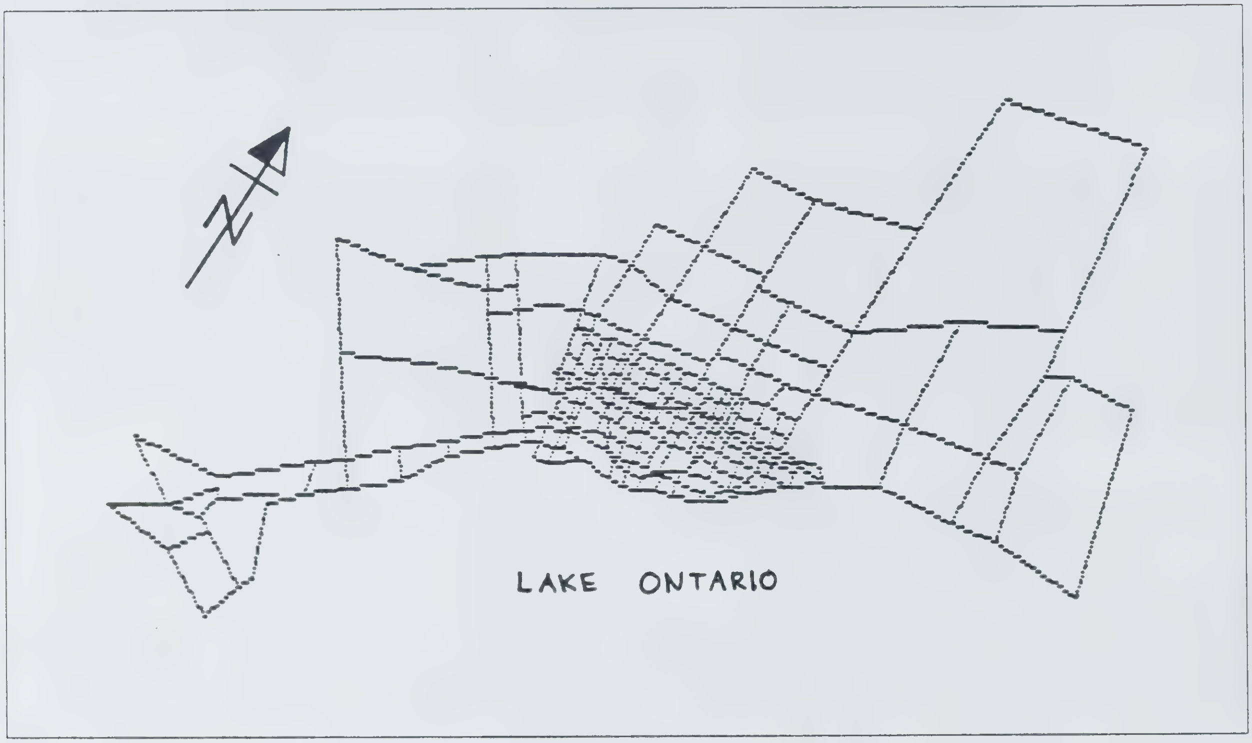
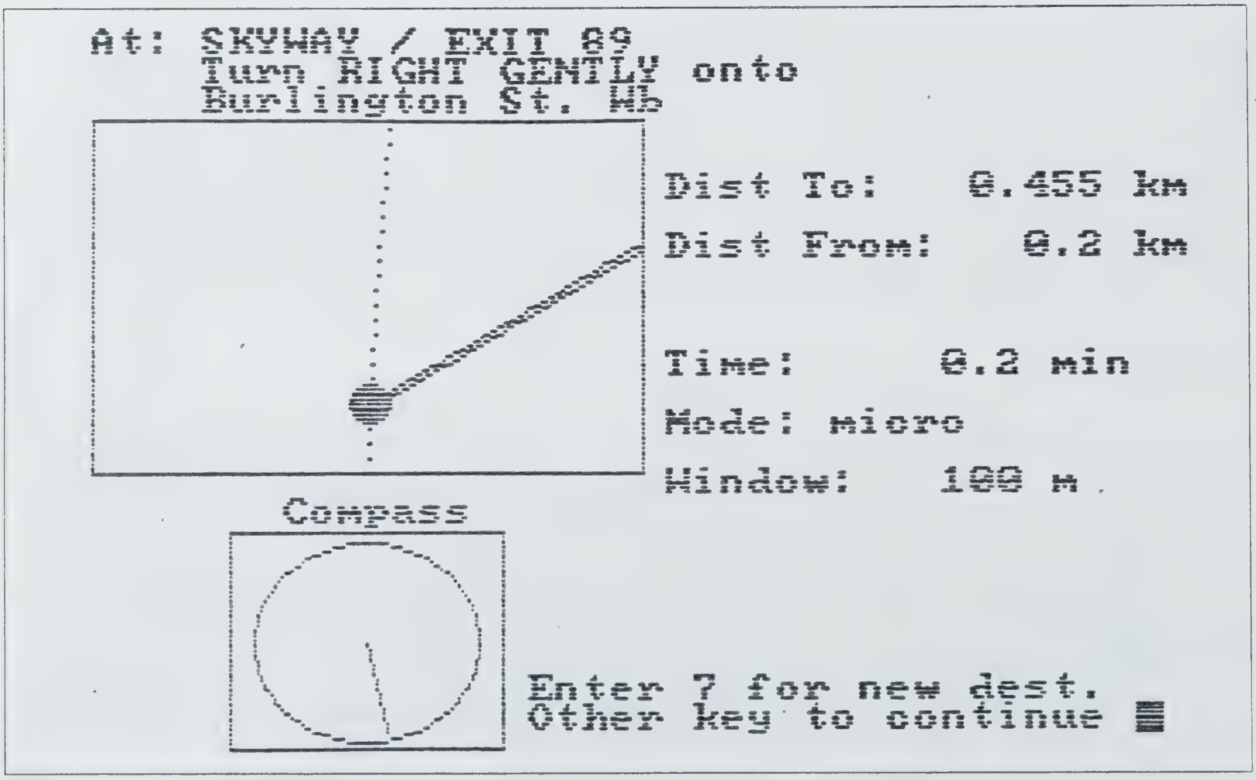


Figure 11b: Sample Q-Route In-Vehicle Display at the Burlington Skyway



b. Q-Route Application for the Burlington Skyway

In order to illustrate the concurrent operation of INTEGRATION and Q-ROUTE, the Burlington Skyway System was set up as a micro network within the macro route guidance network for the entire Greater Toronto Area (GTA), which is illustrated in Figure 11a.

The macro network is utilized to route drivers across the GTA using traffic information about only the major highways and arterials in the area, and it delivers the drivers to the general vicinity of their intended destination. At this stage a micro network routing analysis takes over to deliver the driver to his ultimate final destination. As part of this experiment, the Burlington Skyway was set up as a compatible micro network. Consequently, a driver, who approaches the Skyway, would automatically be routed through the Skyway corridor based on the micro routing results of the INTEGRATION model simulation for that particular time period. This simulation would compute optimum routings in view of other traffic, any incidents and/or any controls.

A sample of the type of information that Q-ROUTE can provide based on the routing vectors that are generated by the INTEGRATION model is illustrated in Figures 11b. Figure 11b illustrates a sample screen that the driver would be faced with when he or she would travel through the Skyway corridor following the occurrence of an incident.

7. CONCLUSIONS

The application of the INTEGRATION model to the Burlington Skyway leads to 5 main conclusions:

First, it is clear that the INTEGRATION model can be a very flexible tool for analyzing the behavior of traffic corridors or networks during congested conditions in view of incidents and their associated response plans. Detailed statistics are available to assist in an examination and understanding of the events that take place following the occurrence of an incident, and show how the operation of the various elements of the necessary response plans can assist in mitigating the incident consequences, either in isolation or in combination.

Second, readily available data from FTMS detectors can be utilized to derive, at a reasonable cost, both the supply and demand data that are required to run the model. Speed-volume data can be analyzed to establish link free speeds, capacities and travel times, while the volume counts for strategic points within the network can be utilized through SODGE to derive the necessary series of O-D demand patterns for the simulation analysis period.

Third, the impact of providing real-time traffic information to all drivers was shown to be of only limited benefit within the Burlington Skyway Corridor prior to the occurrence of an incident. However, following the occurrence of an incident, the re-routing was able to divert some traffic from the congested route onto an alternate route with sufficient spare capacity. The net effect of this re-routing was very significant, in that it was able to reduce network delays to virtually pre-incident values.

Fourth, real-time traffic signal timings, which adjusted cycle times and green splits based on a moving average of traffic volumes, were shown to be able to reduce delays by a significant amount for virtually all incident and non-incident scenarios. The moving average of the traffic volumes could successfully trace the growth and decay in the prevailing traffic patterns, but short-term signal timing fluctuations appeared to be caused by a lack of sufficient damping of random traffic flow variations.

Fifth, the Q-ROUTE system was shown to provide one possible vehicle for disseminating the type of route guidance information that must be communicated to the drivers as part of diversion-based response plans. To this end, both the in-vehicle units and the CMS controller linkage may be employed, but the effectiveness of the latter would obviously depend upon the location of the incident and the diversion point, relative to the location of the CMS.

8. RECOMMENDATIONS

The above 5 conclusions lead to 5 corresponding recommendations for further research, field testing and/or field implementation:

First, the INTEGRATION model should be more extensively tested for other types of incident scenarios and on other types of networks. The results for different scenarios and for different conditions would then allow the formulation of more generalized conclusions about the impacts of incidents and the effectiveness of different incident response measures.

Second, the technique for generating a sequence of synthetic origin- destination counts for a given simulation period should be seeded by either an older planning type of matrix or an approximate matrix as determined by a small survey. Such seeding would result in an improved matrix, while the comparison to actual data would assist in determining more closely the relative magnitude of any current estimation errors within the matrix.

Third, the apparent large reductions in delay through the application of a diversion, in which all drivers were informed instantaneously of changes in network traffic conditions, should be investigated in greater detail. This examination could determine how much of these savings would still be retained, if only a fraction of the drivers were equipped with on-board units, or if the routing information was only provided at certain specific CMS locations within the network.

Fourth, the real-time signal timing procedures utilized within INTEGRATION should be studied in greater detail to determine the relative advantages of utilizing different traffic flow damping weights during the approach flow predictions. This could establish the advantages of having upstream vs. downstream vehicle detectors, to identify changes in approach demands, and to determine the advantages of using uncoordinated vs. coordinated traffic signal controls during congested conditions.

Finally, the Q-ROUTE system should be tested more extensively for applications where multiple diversion routes are available which each have different spare capacities and relative

travel times. These situations would perhaps be more representative of those conditions which are commonly encountered in other integrated networks.

REFERENCES

Blum,Y. and Van Aerde,M. (1989), Traffic Responsive Approach to In- Vehicle Route Guidance using Q-Route, Presentation at the 68th Annual Meeting of the Transportation Research Board Meeting, Washington,D.C.

IBI(1982), Burlington Skyway Freeway Traffic Management System - Queen Elizabeth Way, Preliminary Design Report by IBI to Freeway Traffic Management Systems Section, Ministry of Transportation and Communications, W.P. 85-81-00.

ITE(1984), Canadian Capacity Guide for Signalized Intersections, Institute of Transportation Engineers - District 7 - Canada.

Noxon,G.(1988), Development and Testing of a Model to Estimate Origin- Destination Matrices from Link Counts, Undergraduate Thesis, Department of Civil Engineering, Queen's University, Kingston, Canada.

Delsey,M.J and Stewart,S.E.(1985), Queen Elizabeth Way - Burlington Skyway: Freeway Traffic Management System, Transportation Forum, Vol. 2- 2, 68-72.

Transportation Research Board(1985), Highway Capacity Manual, Special Report 209, National Research Council, Washington, D.C.

Van Aerde,M. and Blum,Y.(1988), Electronic Route Guidance in Congested Traffic Networks, Institute of Transportation Engineers Journal, Vol. 58 - No 8, pp. 33-37.

Van Aerde,M. and Yagar,S.(1988), Dynamic Integrated Freeway/Traffic Signal Networks: A Routing-Based Modeling Approach, Transportation Research, Vol. 22A - No. 6, pp. 445-453.

Van Aerde,M., Voss,J. and Noxon,G.(1989), On-Line Generation of Synthetic Origin-Destination Counts for Application in Freeway Traffic Control, Presentation at the 68th Annual Meeting of the Transportation Research Board Meeting, Washington,D.C.

Van Aerde,M., Voss,J., Case,E.R. and Ugge,A.(1989),Managing Traffic Congestion in Combined Freeway and Traffic Signal Networks, Institute of Transportation Engineers Journal, Vol. 59 - No. 2., pp. 36-42

Van Zuylen,H.J. and Willumsen,L.G.(1980), The Most Likely Matrix Estimated from Traffic Counts, Transportation Research, Volume 14B, pp. 281-293.

Van Zuylen,H.J.(1981), Some Improvements in the Estimation of an O-D Matrix from Traffic Counts, Eighth International Symposium on Transportation and Traffic Theory, University of Toronto, Canada, pp. 183-190.

APPENDIX E:

A COMPREHENSIVE APPROACH TO IN-VEHICLE ROUTE GUIDANCE USING Q-ROUTE

Yuval Blum and Michel Van Aerde

ABSTRACT

The Q-Route route guidance concept was developed with the objective of providing drivers with comprehensive and traffic-responsive route guidance to address-specific network destinations within a large urban area.

The traffic-responsive aspect of Q-Route is implemented using a macro level routing which can consider historic and/or real-time traffic volume and capacity estimates on all freeways, arterials and major collectors in the control area. In its autonomous mode, macro routings, which reflect recurring congestion, are implemented on a time-of-day basis. However, a communications link is required to have macro routings based on real-time traffic flow measurements in order to respond to non-recurring congestion. The driver is delivered to address-specific network destinations using a micro level routing, which considers only the local streets within the immediate vicinity of the driver's final destination. The micro routing is automatically invoked once the driver's destination zone is reached and is intended to guide drivers to the exact local street and street number range within the desired macro destination zone. The combined macro/micro routing procedure is transparent to the user/driver.

The objective of this paper is twofold. It first describes the Q-Route comprehensive route guidance concept and indicates how a Route Guidance System can be integrated with current and future traffic control models to provide consistent routing information through several compatible driver information subsystems. In addition, the paper illustrates the design and implementation of the in-vehicle subsystem of the Q-Route prototype, which was tested in Kingston, Canada using both autonomous and non-autonomous modes.

1. INTRODUCTION

For the purposes of the design of Q-Route, it was considered that drivers within most urban traffic networks belong to one of three subsets of drivers, each of which could benefit significantly from improved route guidance (Van Aerde and Case, 1988).

The first group consists of those drivers who are unfamiliar with the city's road network structure and are unaware of either the exact location of their destination and/or the optimum route towards that destination. Secondly, there are drivers who have a general awareness of the road network structure, as indicated on a standard city map, but who are unfamiliar with the relative amounts of traffic congestion on alternative routes at various times of the day. Finally, there are drivers who are familiar with both the network structure and recurring traffic congestion patterns, but who are unaware of any non-recurring traffic congestion which is unique to that particular time or day.

The ultimate objective of Q-Route is to simultaneously provide improved routing information which can satisfy the needs of drivers belonging to any of the above subgroups. Such a system would reduce excess travel distance/time, decrease the extent of recurring congestion and minimize the impact of non-recurring traffic congestion. Consequently, the emphasis of the Q-Route system is on determining the optimum traffic routings within a traffic network and on effectively communicating this routing information to the drivers. This is distinctly different from similar systems which attempt to accurately establish/trace a vehicle's location and only passively display the amount of traffic congestion on various links throughout the network. Within this paper, the former Q- Route activity is referred to as routing, while the latter is referred to as navigation. It is the opinion of the authors that while navigation may prevent drivers from getting lost, only routing can accomplish the aforementioned travel distance and time savings.

While some of the attributes of Q-Route are similar to those of ALI- SCOUT (Von Tomkewitch, 1986), AUTOGUIDE (TRRL, 1986), and CACS (Fujii, 1986), as all of these systems are ultimately attempting to provide a similar type of service to the driver, the Q-Route concept is seen to be unique for three main reasons. First, Q-Route is intended to disseminate routing information which can be generated using a variety of different traffic control and simulation models. Secondly, the in- vehicle component of Q-Route is intended to be functional in either an autonomous mode, using historical traffic flow patterns, or in a non- autonomous quasi real-time mode, using real-time traffic flow data which are periodically downloaded to the in-vehicle unit to update the default historical routings. Finally, the Q-Route concept is intended to be comprehensive in that it can immediately provide network-wide routing coverage in an urban area and as it can provide consistent routing information using either its in-vehicle, CMS (Changeable Message Sign), or pre-trip planner subsystems. However, as general overviews of Q- Route's CMS and pre-trip planner subsystems were presented earlier, this paper focuses in detail on primarily the core structure of Q-Route's In- Vehicle aspect.

2. Q-ROUTE: A COMPREHENSIVE DRIVER INFORMATION SYSTEM

The Q-Route Driver Information System was first described in Van Aerde and Blum (1988) as a single system which could address the route guidance needs of an urban area and its traffic control system. This is accomplished through the joint control of 3 compatible subsystems, namely:

a) Pre-Trip Route Planners,

b) Changeable Message Signs, and

c) On-Board Route Guidance Systems.

These 3 subsystems may seem very different on the outside in appearance and operation, but, as shown in Figure 1, internally they are all simple variations of the same basic Driver Information System. This is true both conceptually and physically, as consistent route guidance information needs to be assembled and disseminated, and as the same algorithms, hardware and database structures can be relied upon.

a. Routing Vector Concept

The entire Q-Route route guidance concept is developed around the use and sharing of a central set of route guidance vectors (Van Aerde(1985) and Van Aerde and Blum(1988)) by all routing subsystems, as well as by the central traffic control models, which can be used to generate the traffic-responsive routings. The routing vectors indicate the shortest or quickest route from any point in the network (origin node) to any specific network destination (destination node). As illustrated in Figure 2, the vectors indicate for any network node the next street to follow to get closer to one's destination. As this node can be either an origin node, or an intermediate node along the driver's path, one can iteratively re-use the vector at the end of each street or road to proceed incrementally, along the branches of the minimum path tree, towards the desired ultimate destination.

The routing vectors are stored for use in Q-Route in a standard tabular format which lists the optimum next link for each current node. This allows the use of a variety of different procedures to generate these vectors. In addition, regardless of the originating source of these vectors, each of the three Q-Route subsystems can derive its "optimum" routings using these same routing vectors.

For example, as illustrated in Figure 3, the Pre-Trip Planner can trace all the links along the intended path, and list both the turning movements and the distances to them. Similarly, the In-Vehicle Display Unit can display "bird's eye view" maps of each intersection en-route and indicate the optimum turning movement as indicated by the corresponding routing vector entry. Even the CMS controller can use them to select the appropriate freeway exit for a given destination. This shared use of a common routing database is intended to provide more consistent and less expensive routing services within an urban area.

Figure 1: Overview of Q-Route Route Guidance Subsystems

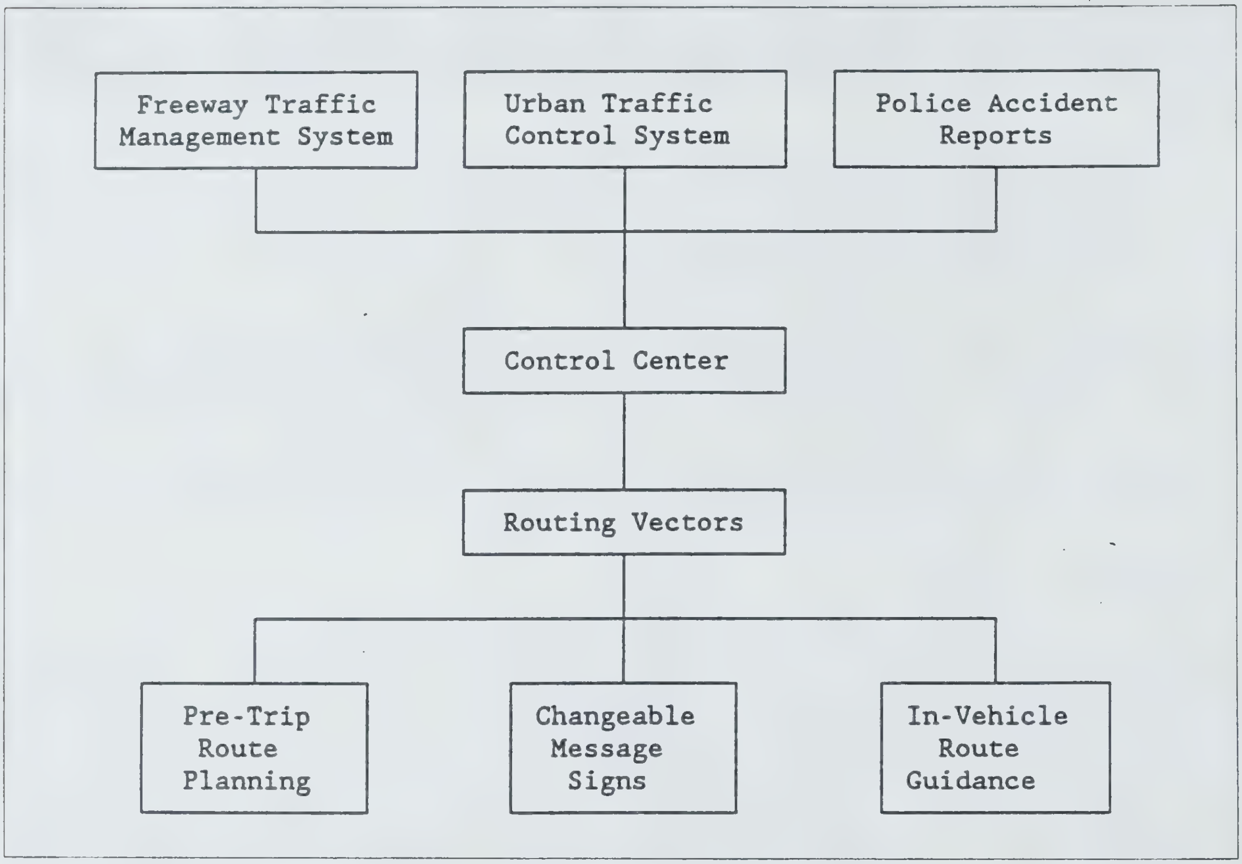


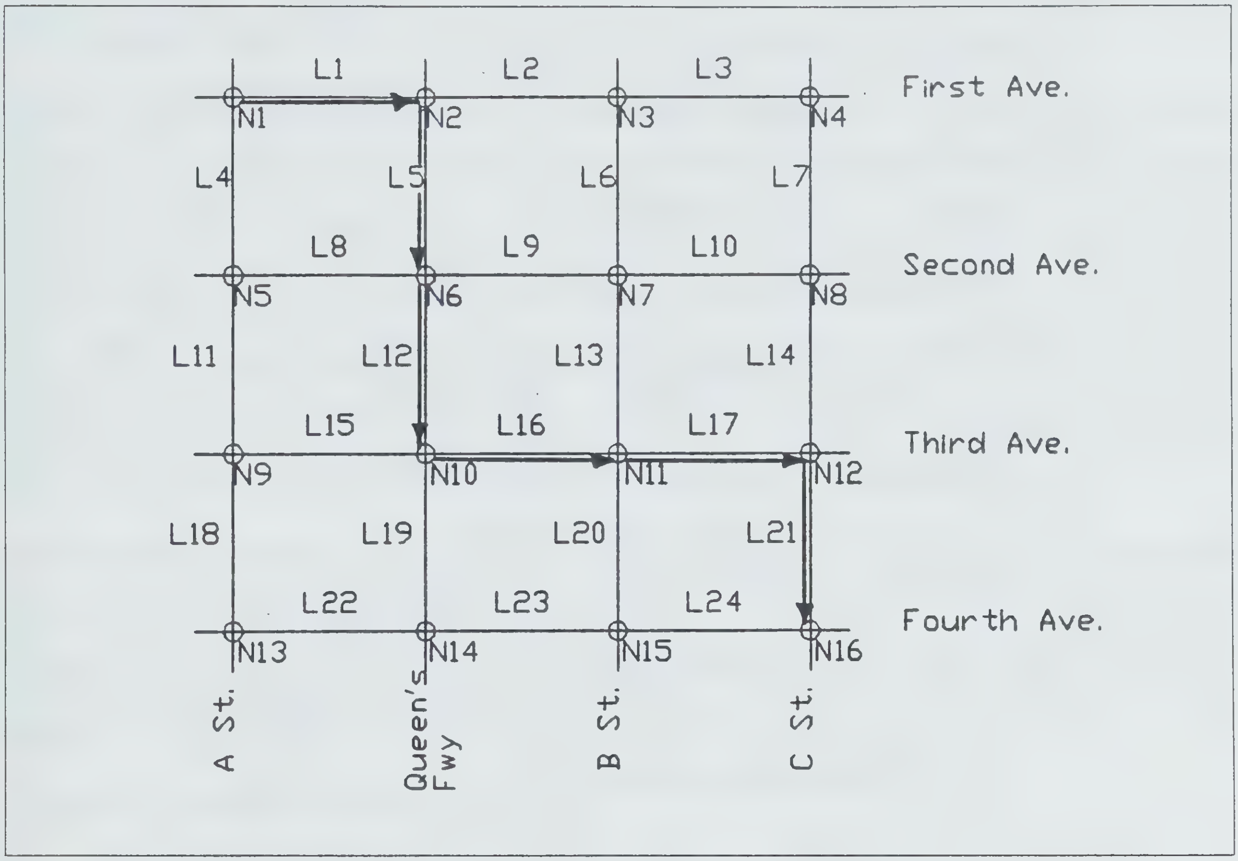
Figure 2a: Routing Vector Representation of Minimum Path Route

Routing Vector Corresponding to Destination N16

Node From	Number of Next Link	Start/End Node of Next Link
N1	L1	N1 -> N2
N2	L5	N2 -> N6
N3	Lx	
N4	Lx	
N5	Lx	
N6	L12	N6 -> N10
N7	Lx	
N8	Lx	
N9	Lx	
N10	L16	N10 -> N11
N11	L17	N11 -> N12
N12	L21	N12 -> N16
N13	Lx	
N14	Lx	
N15	Lx	
N16	0	Destination

Lx - other link number, not relevant to this route.

Figure 2b: Sample Minimum Path of Hypothetical Network

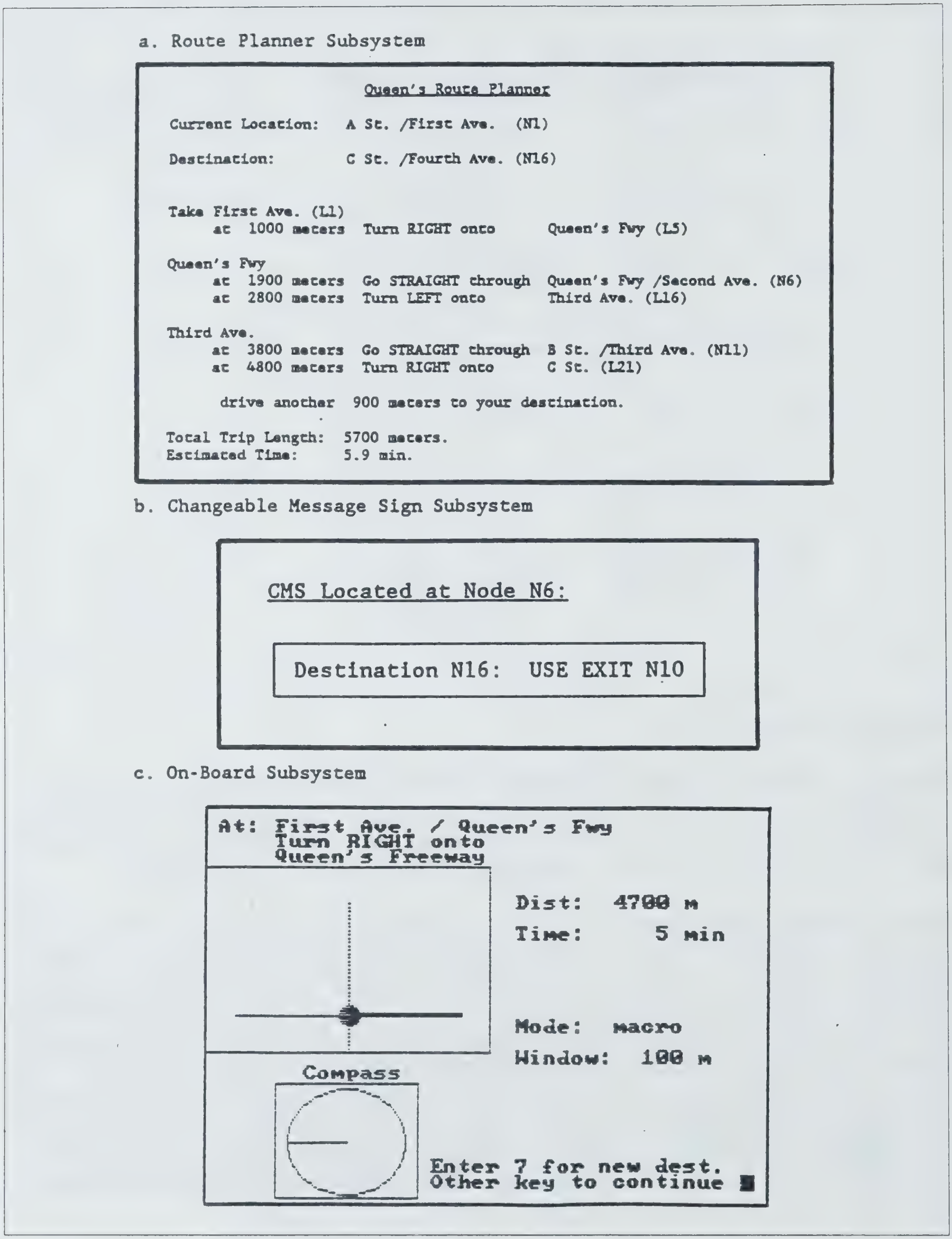


b. Quality of Routing Services

The quality of the route guidance information provided by the three subsystems to the drivers depends not only upon the quality of the traffic model which determines the actual routing vectors, but also on the extent to which this routing vector generator has considered the feedback impact of driver responses to the recommended routings or re- routings.

Therefore, as Q-Route was designed to be compatible with a variety of different traffic models, it can also interface with a very detailed integrated network analysis tool, called Integration(Van Aerde and Yagar(1988a and b), and Van Aerde et al(1989 a,b and c)). In the first instance, this traffic model determines traffic- responsive routings through congested traffic networks in response to changing origin- destination traffic demands, any incidents, queueing, and the prevailing network controls, such as signal timings or ramp metering rates. In addition, the model can consider the impact on the city's traffic pattern of drivers which utilize in-vehicle route guidance units. This then allows the model to estimate the impact of the routed drivers on the rest of the network. Recently, an additional model feature has been added which allows it to consider different percentages of drivers which utilize in-vehicle route guidance systems.

Figure 3: Q-Route Use of Routing Vectors



c. Prototype Testing in Kingston

A typical Q-Route application involves the sequential or concurrent execution of the routing vector generator and a Q-Route routing information dissemination subsystem.

Fully autonomous route guidance can be provided by first generating the required routing vectors off-line and pre-programming these data into the in-vehicle unit. If more than one routing is pre-programmed into the unit, the appropriate one can be selected from this library on a time- of-day or day-of-the-week basis. This type of pre-programmed routing is very similar to fixed-time control of traffic signals, with a similar economy of operation and level of effectiveness. If a communications link exists, traffic routing vectors can be disseminated upon request in real time using approaches parallel those taken to provide real-time traffic signal control. When the routing vectors are calculated on- line, fully traffic-responsive routing can be implemented. At a smaller cost, this same objective can be achieved through a dynamic selection of routings from a library of pre-calculated routing patterns. In either case, the operation of the Q-Route in-vehicle control logic is virtually identical.

As part of the Q-Route prototype testing in Kingston during the summer and fall of 1988, the autonomous mode was evaluated most extensively. However, the use of a communications link, based on a cellular telephone, was also tested. An illustration of the hardware/software configuration of the Q-Route prototype during this testing is illustrated in Figures 4 a and b. The linkages to the computer voice routines(TALK) and the trip origin-destination selection menu(NODEID), as well as to the main data inputs, are illustrated in Figure 4b.

3. MACRO / MICRO ROUTING CONCEPT

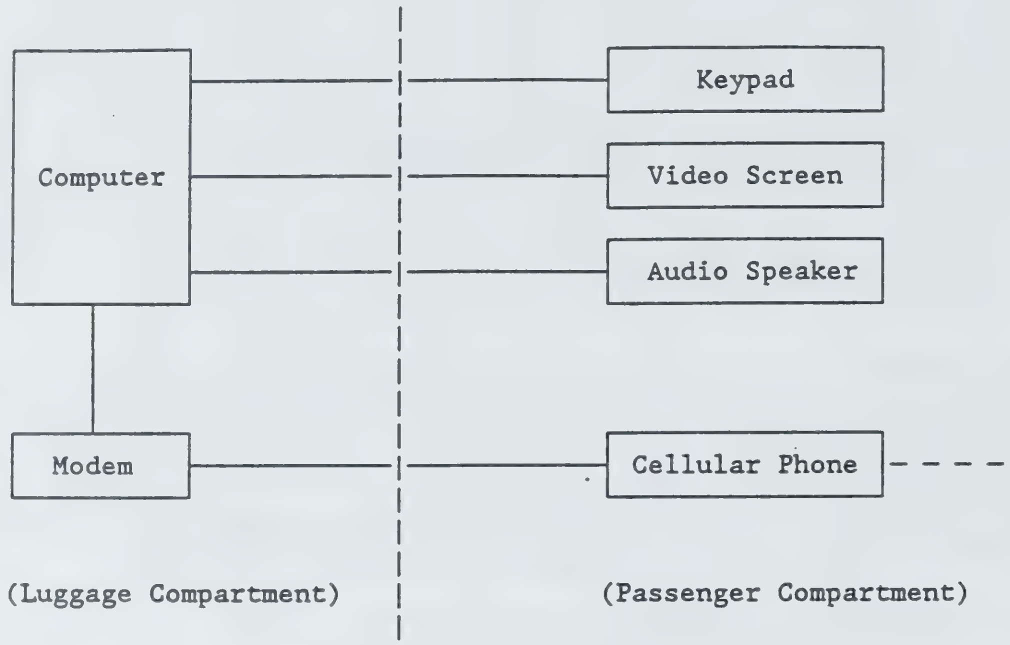
Traffic-responsive routing within large metropolitan areas presents several data management problems due to the number of streets and traffic volumes that may have to be considered in selecting the "best" route between a given origin and destination. Within Q-Route, this problem has been addressed by selecting a driver's trip path based on a sequential macro/micro routing process.

a. Combined Macro/Micro Routing

The macro routing considers only major freeways, arterials and collectors, and provides the driver with a traffic-responsive routing to the edge of the zone of the intended destination. Usually, only the freeways and major streets are considered, as inter-zonal trip makers should be discouraged from travelling through local streets and neighborhoods. These macro network links are likely the only ones to be sufficiently detectorized to support traffic-responsive routing. Furthermore, by limiting the initial macro destination choices to the number of macro destination zones, and restricting the routing choice set to only those links which represent major streets, the macro routing calculation is significantly simplified.

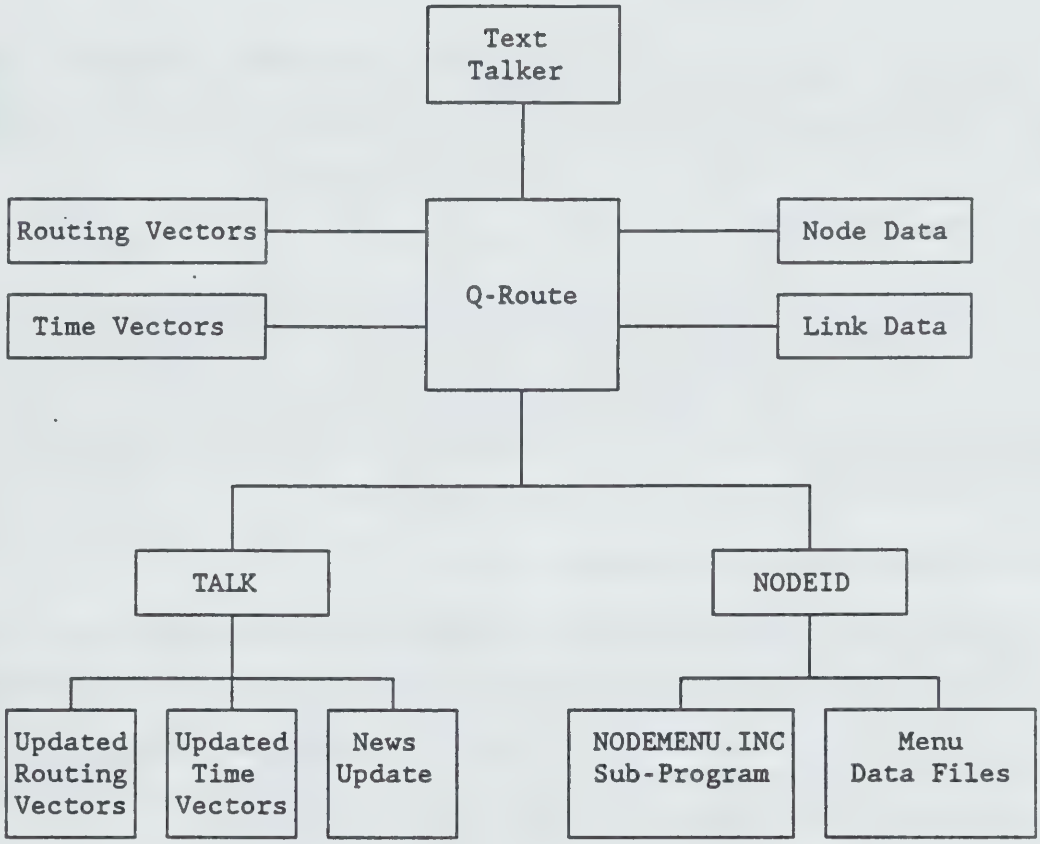
Once Q-Route detects that the driver has reached the periphery of the macro destination zone, a second micro routing is automatically invoked to guide the driver from the zone's periphery to his micro destination within the macro destination zone. This routing finds the quickest

Figure 4a: Q-Route Prototype Hardware during Field Tests in Kingston



Computer	- IBM compatible Personal Computer, 640 Kbytes memory, equipped with hard disk of 40 Mbytes, serial port and co-processor Intel 8087
Keypad	- 6.5 X 5 inch, 23 keys
Video Screen	- 8 inch monochrome graphics screen, 23 rows X 40 col.
Audio Speaker	- with volume control
Cellular Phone	- standard portable cellular phone
Modem	- 1200 baud

Figure 4b: Q-Route Prototype Software during Field Tests in Kingston



Q-Route - Route Guidance Program

Text Talker - Synthetic Speech Software

TALK - Communication Software
(used with cellular phone + modem)

NODEID - Menu Program
(for easy selection of origin/destination)

path from the macro/micro transition node to a specific block on a local street or specific landmark within the zone. The additional micro routing is necessary, as it is unlikely that the macro network will contain either the local street, on which the ultimate trip destination is located, or the local streets which are needed to reach the micro destination. A lack of an ability to deliver the driver to his exact destination would limit the system's potential usefulness, as unfamiliar drivers would still be unable to reach their ultimate destination, even after reaching the general vicinity of their destination.

The links contained within the micro network are unlikely to be fully detectorized. Consequently, the final micro routing is usually performed using pre-programmed link speeds and link lengths. Only when the final micro network is for a congested downtown area would the routing vectors be generated based on a more detailed local analysis.

b. Prototype Testing in Kingston

Figure 5a illustrates the macro network that was utilized during the Kingston route guidance experiment, while Figure 5b illustrates the micro network that was employed to provide micro routing within macro zone 39, which contains the Queen's University Campus. During the tests, micro routings to various macro destination zones within the downtown area were also tested. Typically each of the micro networks contained approximately the same number of links/nodes as the initial macro network for the entire study area.

c. Advantages of Mixed Macro/Micro Routing

The mixed routing approach provides a number of advantages to Q-Route in terms of both the driver and the system. The main advantage arises from the fact that a database containing all the local streets within a city in one network would be prohibitively large. This would likely cause several problems in terms of memory space requirements and execution time for both the on-board unit and the central routing control center. In addition, it would make updating and checking the network database cumbersome, if not impossible.

Q-Route's network partitioning into macro and micro elements also allows the system operator to only provide macro routing coverage for a large commuting area at the outset, while micro networks for critical destination zones can be added as resources permit. It may even be desirable for the ultimate configuration to provide strictly macro level coverage in the suburbs or surrounding towns, and to concentrate the micro routing services in the main commercial, business and tourist areas. The combined macro/micro approach provides this flexibility.

Finally, the use of a macro network en-route avoids the cumbersome reference to local street details, if one is on a cross-city trip using the main freeways or arterials. The reduced information load along the route will allow the drivers to better concentrate on the display when they reach their destination zone and the micro routing is invoked.

Figure 5a: Typical Macro Network Representation and Routing

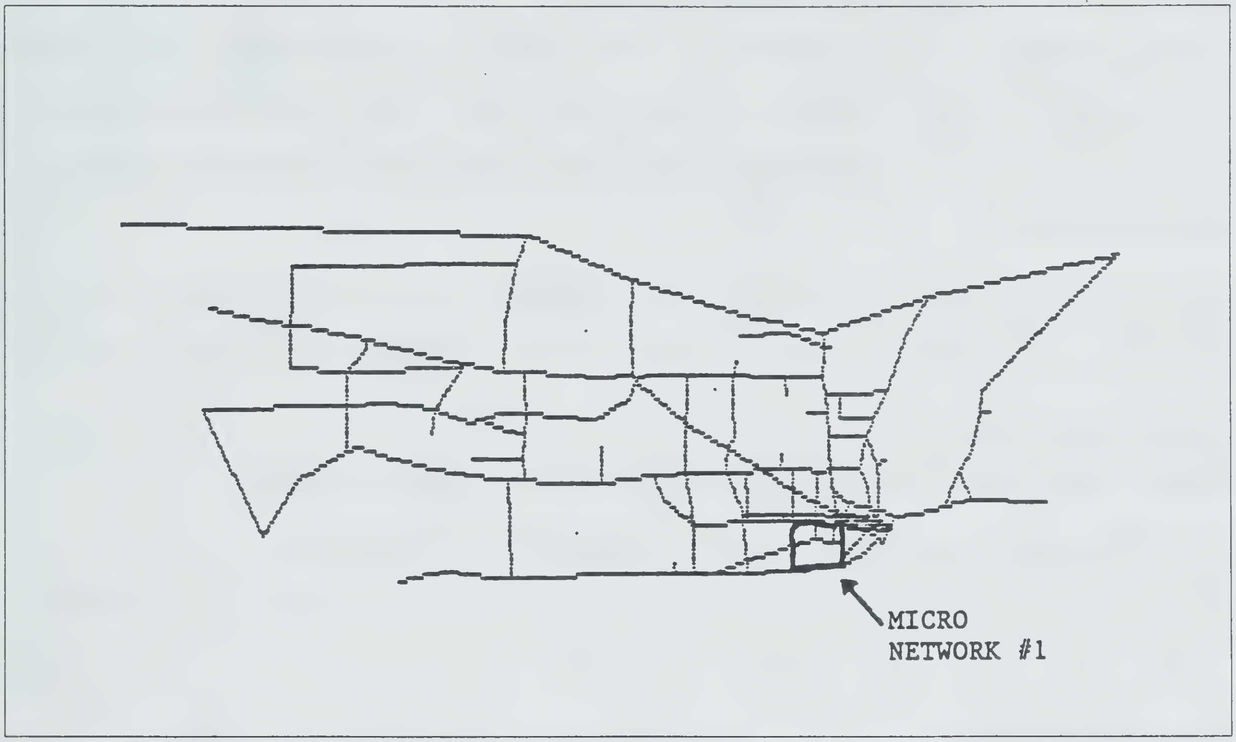
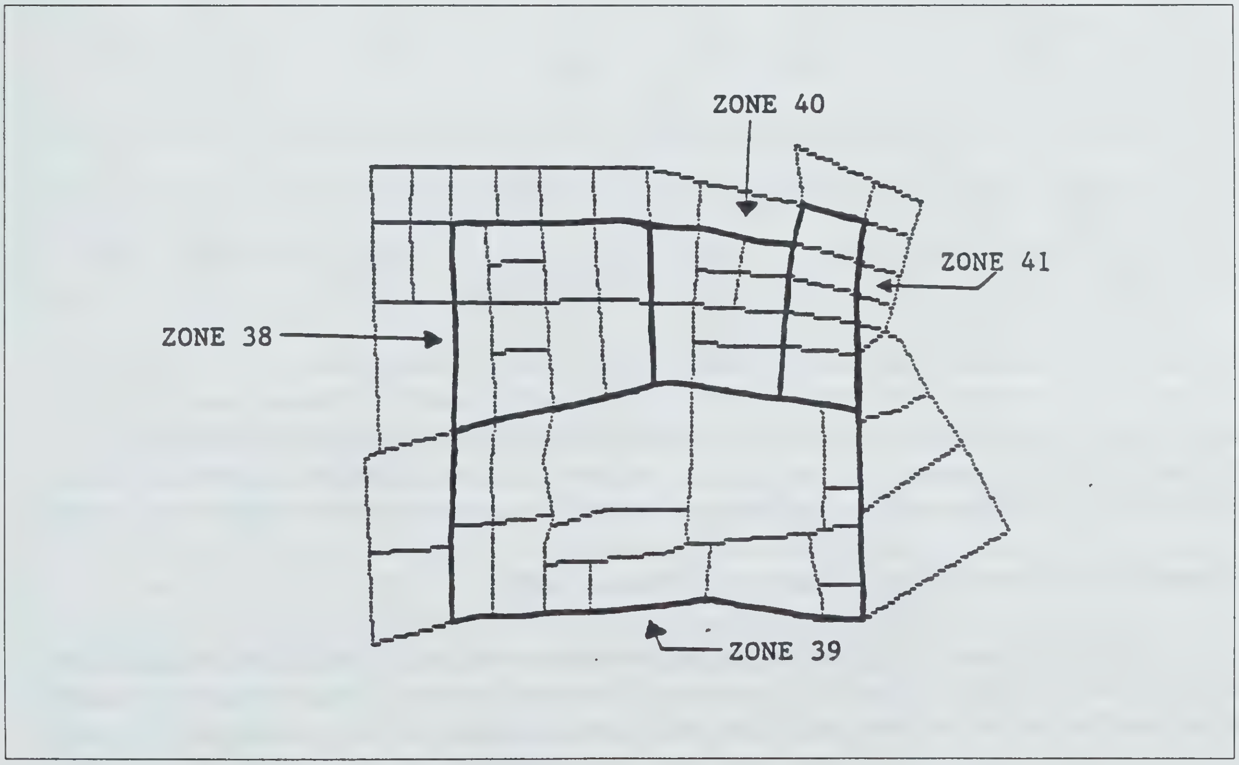


Figure 5b: Typical Micro Network Representation and Routing



d. Switching Between Modes

Within the current version of the Q-Route system, the routing starts with the macro mode and switches automatically to the micro mode if a micro network is available. The actual macro/micro switch is performed at what are called transition nodes. These nodes are destination zone specific, and indicate to the macro routing system that the micro routing network for the destination zone has been reached and that the micro routing can take over. Within this scheme, the locations of the transition nodes are common to both the macro and micro networks.

For each destination zone, there are a number of different transition nodes designated along its boundary. This allows the transition for a given zone to take place at a different location, depending upon which direction the driver arrives from. Consequently, if the traffic- responsive macro routing delivers the driver to the destination zone from a different direction, the driver will still be routed to his/her destination using the most efficient micro route from that point on. In any case, the macro to micro transition is transparent to the user.

It is anticipated that later a super macro mode will be added which will contain all the major streets within a province or state. In this fashion, a super macro routing would first guide the driver to the metropolitan area of interest. Subsequently, the normal macro mode would guide the driver from the boundary of the metropolitan area to the neighborhood of interest. And finally, the micro routing would guide the driver to his ultimate street address within the desired neighborhood.

4. GENERATION OF ROUTING VECTORS

The micro routing is usually derived from strictly static travel time estimates. These travel time estimates are based on the length of the local roads, an estimated average speed for local roads, and an adjustment for any traffic signals, stop or yield signs. In contrast, the macro routing vectors can be made traffic-responsive, if they are calculated using either historical time-of-day link flows, real-time link volumes from detectors, or derived link volumes from a traffic management or a transportation planning model. Of course, if the more sophisticated real-time traffic-responsive data are not available, or if the vehicle is not equipped with a communications link, the macro routing mode can always default to the use of static routings.

The traffic-responsive potential of Q-Route's macro routing derives from its compatibility in structure and concept with different types of related traffic models. This compatibility refers not only to the link and node files, which describe the network topography, but also to the important routing vectors, which are the key to the exchange of traffic- responsive routing information. This relationship to other types of traffic network models is described below.

a. Generation of Routing Vectors using an Off-Line Model

The simplest way of generating Q-Route's macro routing vectors involves the use of an off-line transportation planning model or a freeway corridor control model. Relatively large networks can be handled in this fashion and often such networks have already been coded for other

traffic studies of the same area. In addition, these models can easily be utilized off-line to pre-test different routing scenarios.

Based on this off-line approach, routing vectors for different traffic flow scenarios can be simulated using different origin-destination demands for different times of the day. In each case, the routings can be pre-generated, checked and stored in the form of a library, using either disks, tapes or EPROMS, from which they can be selected on a time-of-day or day-of-the-week basis. When a major construction program takes place within the urban area, the capacities of the affected links can be modified appropriately in the traffic models and a new set of routings developed. Similarly, routings for even one-of-a- kind special events can be quickly derived by modifying the trip generation characteristics of the macro zone in question. However, this approach can only deal with recurring congestion or congestion arising from predictable events.

Hybrid traffic operations/transportation planning models, such as CONTRAM (Leonard et al., 1978), SATURN (Van Vliet, 1982) or INTEGRATION (Van Aerde et al., 1989a,b and c) may be of some further assistance in this respect, as they provide a traffic assignment capability in a traffic management context which reflects local congestion, queueing and signal timings. These models may be utilized either in conjunction with part of the macro network, or for the entire micro network for the destination zone which includes the troublesome traffic generator.

b. Generation of Routing Vectors using On-Line Data

The ideal operation of the Q-Route system would involve its execution based on real-time traffic flow and incident data. Such routings could respond to non-recurring as well as recurring congestion and provide the type of information required by commuters.

The initial step towards the implementation of a traffic-responsive route guidance system would involve the use of on-line traffic flow measurements and incident data to compute in real-time the optimum routings through the network. The traffic demand data would have to be combined from existing FTMS and UTCS detectors, while the incident data would have to be entered by an operator. At this stage, the main obstacle to this type of on-line generation of routing data is in the difficulty of pooling the traffic data for an entire urban area from the numerous traffic authorities which may be responsible for different parts of the traffic network.

The ultimate objective of an on-line route guidance system would involve the use of real-time origin-destination counts, rather than simple real- time link counts (Van Aerde et.al, 1989b). These data, in conjunction with an on-line control model, could pre-determine the expected diversion impact for a given re-routing instruction and establish if the impact of the re-routing could be accommodated by the system. Not only could these vectors be purely reactive, in the sense that they respond to existing traffic problems, but they could become pre-emptive by responding to expected traffic problems before they actually occur (Van Aerde and Case, 1988).

c. Prototype Testing in Kingston

The initial Q-Route prototype was tested using pre-programmed routing vectors which were based on a transportation planning type of analysis of peak and off-peak traffic conditions during a typical day. These routings were then be selected in the autonomous mode based on the time of day. All routings between a given O-D were all-or-nothing based on travel times and a traffic assignment for a network which was already in equilibrium. When the number of routing participants is initially relatively small, these all-or-nothing routings are not likely to disturb the existing equilibrium assignment.

As no computerized traffic control center is in operation in Kingston at this time, it was impossible to properly test the on-line capabilities of Q-Route. However, the general capability was tested by uploading to the mainframe a series of different routing vectors, which were downloaded to the in-vehicle unit through the cellular car phone and a modem. This allowed the testing of both the communications software and the automated data manipulation procedures. It was found that, even when no on-line traffic source is available, the communications link may advise drivers of road conditions and re-route them around construction.

While a separate cellular phone number may need to be set up for approximately every 100 participants in the traffic-responsive mode, this cost should be compared to the cost of installing beacons throughout an entire urban area.

5. ROUTING INFORMATION DISSEMINATION

Q-Route's initial field testing identified a number of issues related to the dissemination of real-time route guidance data. Based on an analysis of these issues, the 2 main types of communication hierarchies, which are illustrated in Figure 6 a or b, appeared to provide feasible implementation approaches.

a. Alternative Communication Hierarchies

Figure 6a shows the first hierarchy in which the Q-Route central control center could process the traffic and routing information and produce the macro routing vectors for each macro destination. In addition, any descriptive messages regarding significant traffic incidents within the system would be generated. These vectors would then be downloaded to the roadside units at each major intersection at pre-specified time intervals. Any vehicle which then passes the roadside unit, would be provided with the routing vector for his specific destination upon request. As the roadside unit could also communicate its location ID, this roadside to vehicle link would therefore also support a form of vehicle navigation.

Within the second Q-Route hierarchy, which is shown in Figure 6b, a central control center could communicate directly with the in-vehicle units through a cellular telephone or another type of radio communication. With this type of communication system, new routings and descriptive messages could be downloaded to the vehicle, but the unit would need to identify its current network location without any external assistance. This is not a problem if the driver follows the recommended route, but may cause problems if an incorrect turning movement is

Figure 6a: Communication Hierarchy - Version I

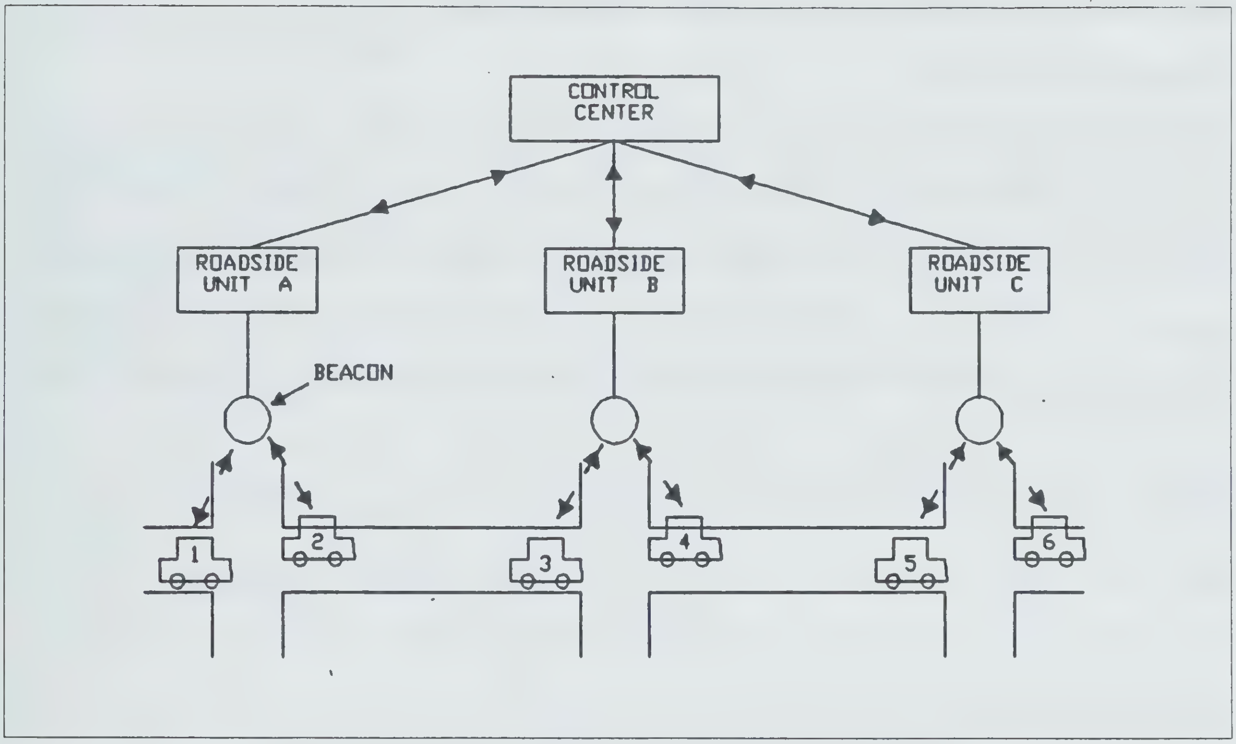
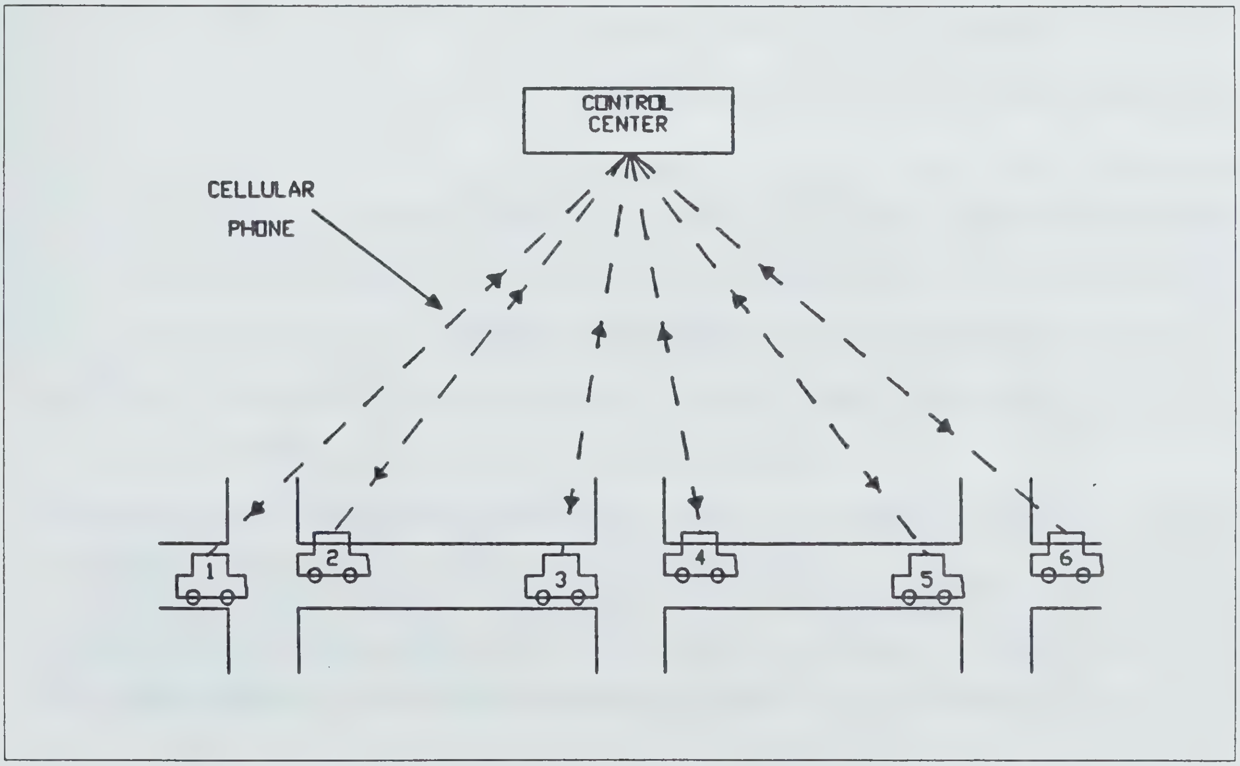


Figure 6b: Communication Hierarchy - Version II



made. In this case, navigation techniques, such as dead- reckoning plus satellite or Loran-C type systems, may be required to re-establish one's network position, such that Q-Route can provide a new routing from the new network location onwards.

b. Communication Links

For the system configuration in Figure 6a, two major communications links must be present. The first link primarily supports the downloading of the routing vectors from the central control center to each roadside unit. Reverse communications from the roadside unit to the central computer would allow the roadside unit to send statistics on the number of user queries back to the control center. These statistics on the number and types of destinations, that were queried by the users, could provide a real-time update of the prevailing Origin-Destination patterns. This communication would likely share existing traffic control communication links to each intersection.

The second link is a two-way communication link between the roadside unit and the in-vehicle computer. It allows the vehicle to request and receive the routing vector for its specific destination. In addition, the roadside unit's ID allows the vehicle to re-establish its network location, if the driver had not followed the recommended route. Q-Route could be implemented using either infra-red beacons or inductive loops to support this two-way exchange of data.

6. DISTRIBUTION OF DATA AND INTELLIGENCE

The type and extent of communications that need to be provided within a route guidance system are intimately related to the distribution of data and intelligence within the system and to the level of routing sophistication that is desired.

a. Extremes in Data/Intelligence Distribution

On one extreme, the central computer could be set up to only download updates of link travel times or impedances and to require the on-board unit to compute the new routings on its own. This requires considerable on-board computational power and also requires the on-board unit to store the entire network database on disk or cassette. However, the amount of data that would need to be transmitted to drivers would be proportional to the number of links in the network, and this data stream would be common to all drivers, regardless of their origin or destination. Consequently, a general city-wide broadcast system would be sufficient and no communications link from the driver to the central computer would be required.

At the other extreme, the central computer could perform all computations and only forward information about the next turning movement to the on-board unit for display, as it passes each intersection. The consequent reduction in computations and data storage requirements would allow for an inexpensive on-board unit, but could require a more extensive deployment of roadside field hardware. Specifically, dedicated communications services would need to be provided at each intersection, and full two-way communications are required in order for the

roadside unit to send the routing instructions which are appropriate for the vehicle's specific destination.

b. Prototype Testing in Kingston

Q-Route experiments to date have involved a compromise in which routings are computed centrally, but the network database is stored on-board. At the start of the trip, the user can either retrieve a routing from its on-board library, or request a new vector for its destination through the cellular phone link. In the latter case, the cellular phone link is utilized to download the routing vector for the intended destination to the unit, and from this point on, both systems operate identically.

During long trips, the routing vector can be updated by request. In this case, the best new route from the vehicle's current location onwards will be selected, but any diversion options that have already been passed will obviously no longer be considered. This flexibility in downloading frequency allows one to trade-off the communication costs involved in each update against the expected benefits.

7. DESIGN OF USER INTERFACE

Critical to the success of any route guidance system are the details of the final user interface design. This section indicates the types of user interface formats that have been considered for use with Q-Route, and discusses the consequent trade-offs involved.

a. Alternative Modes for Presenting the Routing Data

In the ideal Q-Route system configuration, the user would have a colour graphics screen display available for presenting the routing information. This represents the user interface that has been utilized in laboratory experiments to date, and virtually all other types of interfaces are subsets of this ideal.

At the start of the trip, Q-Route provides the driver with a plot of the entire network, with the recommended route highlighted in a different colour. This allows the driver to verify the trip's origin and destination, and provides the driver with a general indication of the intended routing for his trip. As the driver then starts his/her trip, a sequence of timed intersection map snap shots and turning movement instructions are shown for each major intersection along the route. Each such snap shot screen includes the following essential information:

a) a graphics representation the turns at each intersection,
b) a supporting verbal description of the recommended turn movement,
c) a positive identification of the name of intersection,
d) the name of the street / road to be taken or followed,
e) the remaining distance to ultimate destination,
f) the estimated time to ultimate destination, and

g) warning messages which deal with incidents or weather conditions.

In more economical system configurations, the in-vehicle units consist of only simple LED/LCD character displays of the required turning movement messages at each intersection. Alternatively, a directional turning movement indicator can replace the turning messages, and be used in conjunction with another message which identifies the intersection. Each of these alternatives requires a smaller cost to the in-vehicle unit, but also only provide a more limited route guidance message.

b. Prototype Testing in Kingston

During the Q-Route in-vehicle field tests in Kingston, a monochrome composite video monitor in 40 column mode was utilized to simultaneously display both the graphics and text. In addition, a synthetic voice was also included to provide an audio equivalent of the messages provided on the screen. This option was found to be useful during heavy traffic conditions, but problems remained in terms of the quality of the computer voice and its ability to pronounce irregular street names. Prior to commencing the trip, the above video screen and computer voice were also used to provide the driver with a series of hierachical menus in order to assist him in selecting his trip destination. This menu could be accessed by street name/number, by street intersection, by city landmark, or through a directory of services, such as hotels, restaurants, banks, shops, or tourist attractions.

c. Selecting the Appropriate Display Medium

Even for the ultimate user interface, which included a colour graphics screen, finding the right balance between sufficient and excessive information proves to be no simple task. On one hand, there is a tendency to provide the driver with all the information that is known to the central system and that could be of possible interest to the most sophisticated user. However, on the other hand, this ideal amount of information for the sophisticated driver also turns out to be too much information for the less sophisticated driver. Such a driver either becomes lost in the wealth of information that is provided, or becomes distracted to present a safety hazard to others as well as to himself.

The cost of the display is intimately related to its resolution and quality. Experiments to date have shown that multi-color displays are clearly the most attractive and interesting, but that in routine application of the unit, those benefits may not warrant the extra cost. Even for a given display hardware configuration, considerable flexibility remains as to the actual format of the display. Consequently, 3 types of display formats are undergoing user testing. All of these directional displays conspicuously indicate to the user the recommended turning movement at each intersection.

d. Alternative Screen Messages

The simplest version of the display is illustrated in Figure 7a and consists of a directional arrow on the screen. This is a very simple display illuminates 1 out of 8 arrows, which indicate the recommended turning movement to within a 22.5 degree angle. This display can also be

implemented without a video screen, but then needs additional hardware to display the accompanying messages.

Improved routing information is provided using an intersection display which provides an abstract bird's eye view of all the streets which meet at the current intersection, as illustrated in Figure 7b. In this case, the turning movement direction is superimposed over the shape of the intersection, which provides the driver with the relative angle of the recommended road relative to the other roads at the intersection. This mode requires either a low-or medium resolution graphics display, and it was used most extensively during the Kingston experiments.

The highest quality message is produced using a full graphics display, as shown in Figure 7c. In this case, the driver is presented with a localized electronic map which is centered at the next intersection and is rotated to show the crossing roads and any nearby streets in the same orientation as they are seen from the car. A zoom capability has been added to provide both small or large scale views of the area on the graphics screen. The computations involved in this display are much more complex than in either of the above displays, and while useful in the lab, this display was found impractical in the vehicle.

Drivers interact with the above display using a simple keypad. The arrow keys are utilized during the origin-destination selection process, while the function keys can retrieve special weather/news information.

8. SUMMARY AND CONCLUSIONS

This paper discusses the development and prototype testing in Kingston of the Q-Route route guidance approach, to collecting, processing, distributing and presenting traffic-responsive route guidance information.

a. Role of Routing Vectors

At the core of the Q-Route approach is the use of routing vectors which can be created from a number of different sources and can be presented on-board to the driver in a number of flexible formats. The range of compatible options, for generating and disseminating the route guidance information, allows for a gradual implementation of the entire system in compatible stages, while the direct link to models such as the Integration simulation model allows for direct testing of any feedback effects.

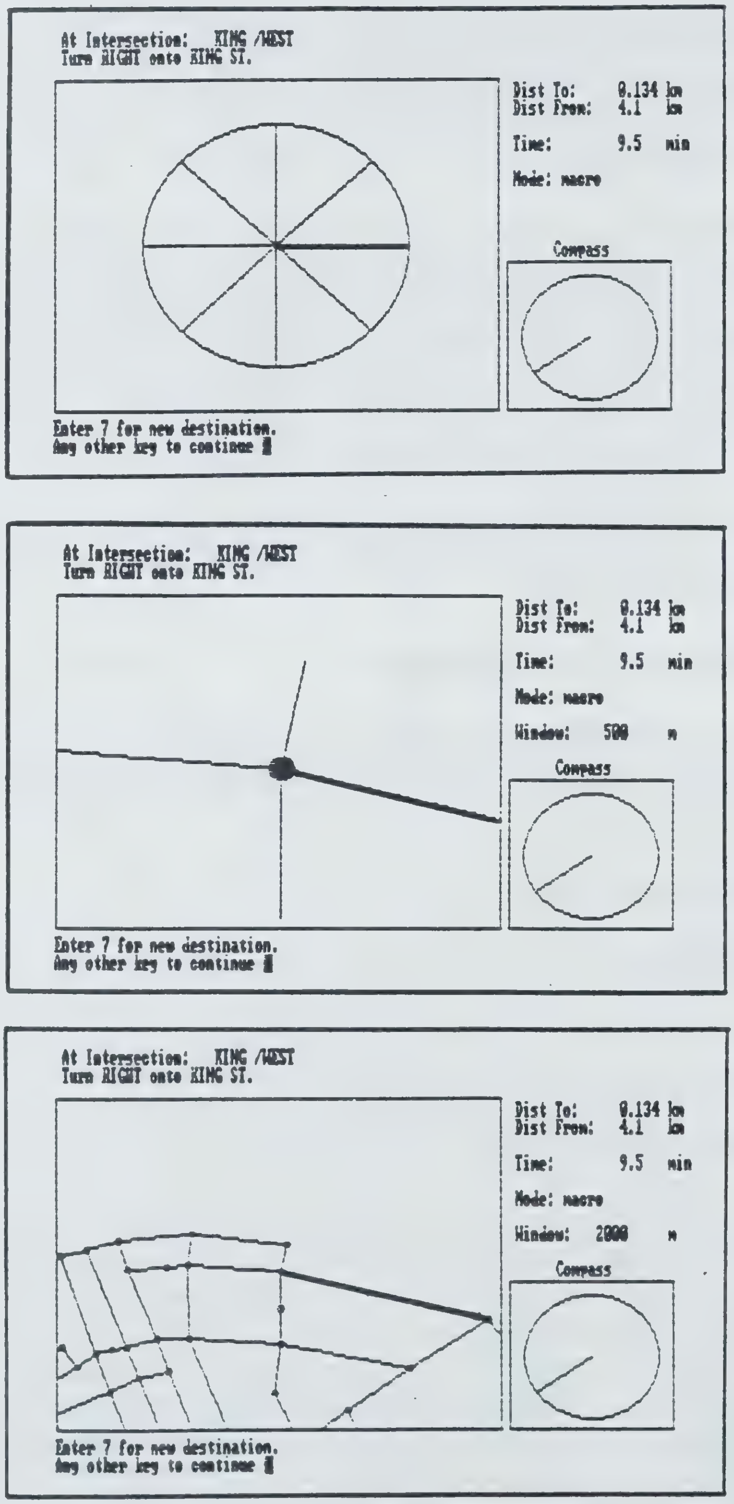
At this stage, the routing vectors provide all-or-nothing assignments to the Q-Route users, and it is assumed that their routings do not influence the network's traffic assignment equilibrium. However, as a larger fraction of the drivers become Q-Route users, it will be necessary to provide multi-path routings which explicitly take into account the impact of the Q-Route routing vectors on the network equilibrium. Ultimately, the routing vectors may be generated in such a fashion as to permit pre-emptive routing strategies, which prevent anticipated traffic congestion, rather than strictly respond or react to traffic congestion which has already materialized.

Figure 7: Alternative User Interface Display Formats

a. Arrows Display

b. Intersection Display

c. Graphics Display



b. Combined Macro/Micro Routing

The combined macro/micro routing concept permits fully traffic- responsive route guidance within large urban areas using a network of all freeways and major arterials/collectors. This network and its characteristics may be derived from transportation planning networks, while traffic volume and travel time estimates may be derived from either historical or real-time FTMS and UTCS data. Of course, in its autonomous mode, Q-Route can only respond to recurring traffic congestion, as a communications link is required to receive updated routings which are responsive to non-recurring traffic congestion.

The complementary micro routing within each destination zone provides further destination-specific instructions to guide the driver to a specific street and street number range. This local routing is usually not traffic-responsive, in view of the lack of the required traffic data, but this is not seen to be a significant limitation of the system. The micro routing is especially important to visitors and tourists within the area, but may eventually also assist to guide commuters and shoppers to available parking lots.

Ultimately, a super macro network may be available for the entire province, state or country, which automatically switches to the available macro and micro networks for each city as the vehicle is being detected on the periphery of the latter networks.

c. Route Guidance Data and Standards

Critical to the successful implementation of a system such as Q-Route is the availability of comprehensive traffic data for all parts of an urban area, regardless of who has legal jurisdiction in each sub-network. In addition to the administrative obstacles, the technical aspects of such data integration in an off-line or on-line mode may impose some other difficulties, which are by no means unique to Q-Route.

In addition, standards need to be established for the development of route guidance databases, communication protocols and hardware/software. Without such standards, it would appear unlikely that drivers would purchase systems which they could not utilize in other cities, towns, or states/provinces within the same country. However, as in any emerging new technology, standards may negatively impact the application of new technology as it becomes available, which may result in standardization based on an obsolete technology.

d. Integration of Routing and Navigation

Q-Route's current prototype implementation only assists in selecting the most efficient route from a known location to either a known or unknown destination, and assumes that drivers follow this route at all times. Before a more full-scaled experiment can take place, an affiliated navigation system may need to be incorporated to deal with drivers who fail to follow the recommended route and get lost. At this time, the system is capable of providing new routings

when a driver gets lost, but it is unable to establish on its own that the driver has drifted from the recommended path.

e. Current Research

At present, current route guidance research is concentrated on more extensive field testing of Q-Route in the Greater Toronto Area, on the evaluation of the benefits of route guidance during different types of recurring and non-recurring traffic congestion, and on the opportunities for providing micro route guidance on freeways with core and collector lanes, such as Highway 401 in Toronto, Ontario (Van Aerde et al, 1989 a, b and c).

REFERENCES

Fujii H. (1986), The CACS Project and Now: Dynamic Route Guidance as the Final Target, 65th Annual Meeting of the Transportation Research Board, Washington, D.C., January.

Leonard D.R., Tough J.B. and Baguley P.C. (1978), CONTRAM: A Traffic Assignment Model for Predicting Flows and Queues During Peak Periods, TRRL Report 841, Transport and Road Research Laboratory, England.

Transport Canada(1985), Freeway Management for Transportation Efficiency and Energy Conservation, Transport Canada Publication TP 6343E, Transportation Development Centre, Montreal, Canada.

Transport and Road Research Laboratory (1986), AUTOGUIDE: A Better Way To GO ?, Department of Transport Discussion Document, London, England.

Van Aerde M. (1985), Modelling of Traffic Flows, Assignment and Queueing in Integrated Freeway/Traffic Signal Networks, Ph.D Thesis, Dept. of Civil Engineering, University of Waterloo, Waterloo, Canada.

Van Aerde M. and Blum Y.(1988), Electronic Route Guidance in Congested Networks, ITE Journal, Vol. 58, No. 8, pp. 33-37, August.

Van Aerde M. and Case E.R. (1988), Individual Driver Route Guidance Systems and the Implications for Traffic Control, Canadian Journal of Civil Engineering, Vol. 15, No. 2, pp. 152-156, April.

Van Aerde,M. and S. Yagar(1988), Dynamic Integrated Freeway/Traffic Signal Networks: Problems and Proposed Solutions, Transportation Research-A, Vol 22A-6, pp.435-443.

Van Aerde,M. and S. Yagar(1988), Dynamic Integrated Freeway/Traffic Signal Networks: A Routing-Based Modelling Approach, Transportation Research-A, Vol 22A-6, pp.445-453.

Van Aerde M., Voss J., Case E.R. and Ugge A. (1989a), Managing Traffic Congestion in Combined Freeway and Traffic Signal Networks, ITE Journal, Vol. 59, No. 2, February.

Van Aerde,M., J. Voss, Y. Blum(1989b), Modelling the Burlington Skyway During Recurring and Non-Recurring Congestion, Engineering Foundation Conference- Traffic Control Methods, Santa Barbara, February.

Van Aerde,M., J. Voss, and G. Noxon(1989c), On-Line Generation of Synthetic Origin-Destination Counts for Application in Freeway Corridor Traffic Control, Annual Meeting of the Transportation Research Board, Washington, D.C.

Van Vliet D. (1982), SATURN - A Modern Assignment Model, Traffic Engineering and Control, Vol. 23, pp. 578-581, December.

Von Tomkewitch R. (1986), ALI-SCOUT - A Universal Guidance and Information System for Road Traffic, Second IEE Conference on Road Control, London, England, April.